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The IMF-World Bank Climate Policy Assessment Tool (CPAT): A Model to Help Countries Mitigate Climate Change

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Authorized for distribution by Dora Benedek

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ABSTRACT: To stabilize the climate, global greenhouse gas emissions must be cut by 25 to 50 percent by 2030 compared to 2019. Such an unprecedented rate of decarbonization necessitates climate mitigation policies across countries, notably carbon pricing, fossil fuel subsidy reform, renewable subsidies, feebates, emission rate regulations, and public investments. To design and implement effective, efficient, and equitable policies, governments need tools to assess economic, environmental, fiscal, and social impacts. To support this effort, the IMF and World Bank are making their joint Climate Policy Assessment Tool (CPAT) available to governments. CPAT is a transparent, flexible, and user-friendly model covering over 200 countries. It allows for the rapid quantification of impacts of climate mitigation policies, including on energy demand, prices, emissions, revenues, welfare, GDP, households and industries, local air pollution and health, and many other metrics. This paper describes the CPAT model, its data sources, key assumptions, and caveats.

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* More details about CPAT, including details on gaining access for governments, can be found at the accompanying webpages of the IMF (www.imf.org/cpat) and World Bank (link available on the IMF webpage). The authors would like to thank current and former World Bank members of the joint CPAT team for the partnership and collaboration, including but not limited to: Dirk Heine, Stephane Hallegatte, Jean-Francois Mercure, Daniel Bastidas, Alexandra Campmas, Ira Dorband, Faustyna Gawryluk, Olivier Lelouch, Helene Naegele, Christian Schoder, Paulina Schulz, Stephen Stretton, and several others. In addition, the team are grateful for the input of several internal and external contributors without whom this work would not have been possible – a list can be found on the above webpages. Lastly, the authors are grateful to James Roaf, Dora Benedek, and numerous IMF colleagues for extensive comments and to Danielle Minnett, Hope Samiee, and Monique Valle for first rate research assistance.

WORKING PAPERS

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Prepared by Simon Black, Ian Parry, Victor Mylonas, Nate Vernon, and Karlygash Zhunussova[1]

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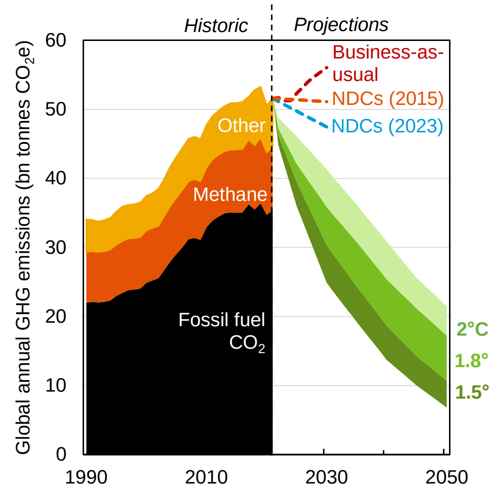
1. Background

Stabilizing the global climate requires rapid cuts in greenhouse gas (GHG) emissions this decade (Figure 1). Achieving the Paris Agreement's target of limiting global warming to 1.5 to 2^{o}C above pre-industrial levels requires cutting global emissions of carbon dioxide (CO_2) and other GHGs by 25 to 50 percent below 2019 levels by 2030 (green areas of Figure 1), followed by a rapid transition to 'net zero' emissions sometime shortly after 2050. To date, around 130 countries—accounting for about 90 percent of global GHG emissions—have proposed or set targets to be 'net-zero' emitters sometime around mid-century.[2]

Figure 1. Global GHG Emissions, Nationally Determined Contributions (NDCs), and Temperature Targets



Sources: IMF staff using CPAT and IPCC (2022).
Note: Excludes land use, land-use change, and forestry (LULUCF) emissions. BAU = business as usual; CO_2 = carbon dioxide; GHG = greenhouse gas.

However, the world is not yet on track to 'net zero': major gaps in climate mitigation ambition and implementation persist. Even if the long-term 'net zero' targets are met, emissions targets for 2030 enshrined in countries' nationally determined contributions (NDCs) are not sufficiently ambitious. Though some progress on ambition has been made since the Paris Agreement's signing in 2015, current NDCs would only reduce emissions by about 12 percent by 2030 compared with 2019. This is less than half of the emissions cuts needed for 2^{o}C and less than a quarter of the emissions cuts needed for 1.5^{o}C warming. What is more, current policies fall even shorter: though emissions have been somewhat flat since 2019 due to the COVID-19 pandemic, global economic slowdown, and the rise in fossil fuel prices, they are likely to rise by 5 percent in 2030 compared with 2019 under the business as usual (BAU) scenario, without new (or a tightening of existing) policies.[3]

Policy reforms are urgently needed across all countries to narrow climate mitigation ambition and implementation gaps. Limiting warming to 2^{o}C above pre-industrial levels (the less ambitious target) requires new measures equivalent to a global average carbon price exceeding $75 per ton of CO_2-equivalent (CO_2e) by 2030, while the current price from explicit carbon pricing schemes is only $5 per ton CO_2e. Additionally, fossil fuel subsidies (accounting for undercharging for both supply and environmental costs) were estimated at $5.9 trillion in 2020, equivalent to 6.8 percent of global GDP[4].

What is holding back policymakers from implementing needed policies? While political economy obstacles to mitigation policy can be significant, part of the explanation is the prevalence of pervasive gaps in knowledge and data. Many government departments lack knowledge about climate policies and their impacts. These knowledge gaps, in turn, contribute to climate policy implementation gaps.

New tools are required to assist policymakers in designing, assessing, and implementing reforms to accelerate a 'just transition'. Designing and implementing effective and sustained climate mitigation policies requires quantitative, evidence-based analysis, with country-level assessments of their impacts. This includes impacts on the energy system (supply, demand, and prices); CO_2 and other GHG emissions; revenues from existing and new energy taxes; economic output; as well as on household and industry incidence. It requires an assessment of the tradeoffs among instruments including carbon taxes, emissions trading systems (ETSs), electricity or individual fuel taxes, emission rate and energy efficiency regulations, feebates, renewables subsidies, public investments, and other policies. However, no tool has previously allowed for such estimation with near comprehensive country coverage.

[2] See: www.zerotracker.net .

[3] See Black and others (2022b).

[4] See Parry and others (2021c).

The IMF-World Bank (WB) Climate Policy Assessment Tool (CPAT) is a spreadsheet-based 'model of models'. It allows for the rapid estimation of effects of mitigation policies for over 200 countries.[5] CPAT is the result of a multi-year collaboration between IMF and WB staff. It evolved from an earlier IMF tool which has been significantly upgraded over time[6] and further improvement is envisaged.[7]

CPAT helps governments design and implement climate mitigation strategies. It allows for:

- **Quantification of many impacts…** This includes impacts on energy production, consumption, trade, and prices; emissions of local and global pollutants including reductions needed to achieve NDCs; GDP and economic welfare; revenues; industry incidence (across many sectors); household incidence (across deciles, urban vs. rural samples, and horizontal equity); and development co-benefits (local air pollution and health impacts). This allows for assessment of tradeoffs (e.g., among efficiency, equity, or administrative burden) and, hence, tailoring of policy design to each country's context.
- **…for many climate mitigation policies...** CPAT can evaluate mitigation policies including carbon taxes, ETSs, fossil fuel subsidy reform, energy price liberalization, electricity and fuel taxes, removals of preferential VAT rates for fuels, energy efficiency and emission rate regulations, feebates, clean technology subsidies, and, most importantly, combinations of these policies ('policy mixes').
- **…for many countries...** CPAT covers over 200 countries accounting for more than 95 percent of global GHG emissions. CPAT's input data is complete and there is no need for external data inputs (though the user has the option of incorporating their own data or parameter assumptions).
- **…in a transparent, user-friendly, and consistent framework.** Results are presented rapidly via a chart-driven interface, allowing for experimentation (and sensitivity analyses) in designing new policies or assessing existing proposals and quick incorporation of results into reports.

Additionally, CPAT contributes to national and global analysis by:

- **Emphasizing the importance of a 'just transition' through estimation of impacts on poverty, equity, and welfare across income groups and between urban and rural households.** It is increasingly recognized that mitigation policies should support vulnerable households. CPAT estimates impacts on households from changes in energy and non-energy prices, both across consumption deciles (vertical equity), within deciles (horizontal equity), and between urban and rural sub-groups.
- **Approximating the best available science.** CPAT is parametrized to be broadly in the mid-range of ex ante models and parameterized to ex post empirical literature. The model is streamlined, with transparent underlying parameters which are readily adjustable for sensitivity analyses.
- **Allowing for cross-country analysis, including through quantitative comparisons of all NDCs.** The model allows for consistent comparisons of mitigation ambition for over 200 countries, including all signatories of the landmark 2015 Paris Agreement (194 countries). Most signatories of the Paris Agreement have quantifiable emissions targets and CPAT converts these to a single, comparable metric (required emissions reductions vs. BAU). This can help countries compare mitigation ambition and effort and inform processes under the United Nations Framework Convention on Climate Change (UNFCCC) and in the design of international carbon price floors and climate clubs.[8]
- **Collating new, comprehensive datasets**: CPAT contains and contributes to new global datasets, including energy consumption and prices; GHGs; local air pollutants; price and income elasticities; environmental costs; and NDCs. It also includes comparable decile-level data on household consumption of energy and non-energy goods for more than 65 countries—one of the largest

[5] CPAT is being made available to governments for internal use – more details can be found at www.imf.org/cpat.

[6] See, for example, IMF (2019a, 2019b), Parry and others (2020, 2021b). Upgrades include increased coverage of sectors, fuels, GHGs, policies, and metrics; a new module for estimating distributional effects across household consumption groups and industries; a new module for assessing development co-benefits of mitigation (e.g., improvements in health and welfare from cleaner air); and more sophisticated parameterization (see Annexes).

[7] This paper describes the first version of the model ('CPAT 1.0'). Future versions may include improvements in sectors, impacts, and policy mixes – see Box 1 for upgrades currently envisioned.

[8] See Parry and others (2021a)

household budget survey (HBS) harmonization efforts to date. Lastly, CPAT includes new datasets from the IMF's Climate Change Indicators Dashboard[9] and spreadsheets accompanying IMF products.[10]

CPAT has been used extensively by IMF staff for climate mitigation policy analysis (see Annex IV – CPAT Applications for a list of examples). This includes:

- **Country-level analyses** produced as part of the IMF's regular economic consultations with countries (Article IV Reports),[11] country-specific working papers,[12] technical assistance,[13] Climate Macro Assessment Programs (CMAPs),[14] and in support of the Resilience and Sustainability Trust (RST).
- **Regional analyses**, for example on needed policies[15] and impacts of global energy price shocks.[16]
- **Global analysis** on the implications of the global economic crisis for mitigation,[17] gaps in global climate policy and options for scaling-up action equitably,[18] and proposing an international carbon price floor.[19]
- **Thematic policy analyses**, notably for the IMF's new Staff Climate Note (SCN) series,[20] such as quantified comparisons of mitigation instruments (e.g., carbon taxes and ETSs),[21] fossil fuel subsidy reform,[22] methane taxes,[23] and the carbon price equivalence of mitigation policies.[24]
- **Training,** e.g. the "Macroeconomics of Climate Change" by IMF Institute for Capacity Development.[25]

CPAT is part of a growing climate policy analysis toolbox. CPAT is the most comprehensive multi-country climate mitigation model available (in country, policy, and effect coverage), but no model can answer all policy questions. Dynamic stochastic general equilibrium (DSGE), computable general equilibrium (CGE), agent-based, and macroeconometric models can further examine economic impacts. Multi-region input-output (MRIO) frameworks can estimate international impacts. Innovation and engineering models can assess technological effects. Lastly, climate-economy interactions – beyond the scope of CPAT's 15-year horizon – can be examined by integrated assessment models (IAMs).

This paper summarizes the methodology behind the first iteration of CPAT ('CPAT 1.0') including its mathematical representation, functional forms, data sources, and key parameter values. The rest of the paper is organized as follows. Section 2 overviews CPAT's structure. Section 3 outlines the mitigation module, which estimates energy, emissions, and economic impacts of policies. Section 4 outlines the distribution module, which allows for household and industry incidence analysis. Section 5 outlines the two co-benefits modules: air pollution and transport. Section 6 concludes. Key caveats are provided under each Section. More detailed descriptions of the modules can be found in the Annexes.

[9] Including NDCs, emissions projections, and fossil fuel subsidy estimates – see https://climatedata.imf.org/

[10] See https://www.imf.org/-/media/Files/Topics/Environment/energy-subsidies/fuel-subsidies-template-2022.ashx for estimates of explicit and implicit fossil fuel subsidies in Parry and others (2021c).

[11] Including for Belgium (Vernon 2023), Canada (IMF 2021a), Greece (IMF 2022b), Korea (IMF 2021c), Peru (IMF 2023b), Philippines (IMF 2022c), South Africa (IMF 2022d), Thailand (IMF 2022e), and Vietnam (IMF 2022f).

[12] Including for Canada (Parry and Mylonas 2017), Denmark (Batini and others 2020), Finland (Wingender and Parry 2021), Germany (Black and others 2021c), Mexico (Black and others 2021a), Netherlands (Batini and others 2021), and Türkiye (Parry and others 2023a), among others.

[13] For example, Chile (IMF 2023a).

[14] For example, Madagascar (Cerra and others 2022).

[15] For example, Regional Economic Outlooks for Latin America (IMF 2021b), Departmental Papers for the Middle East (Anderson and others 2022),

[16] For example, for European countries (Ari and others 2022, Arregui and others 2022) and distributional analyses for Asia and the Pacific (Alonso and Kilpatrick 2022).

[17] Black and Parry (2020).

[18] Black and others (2021c, 2022a, 2022b).

[19] Parry and others (2021a) and IMF (2022a).

[20] See: https://www.imf.org/en/Topics/climate-change/staff-climate-notes

[21] Black and others (2022a).

[22] Parry and others (2021c) and Parry and others (2023b).

[23] Parry and others (2022b).

[24] Black and others (2022a).

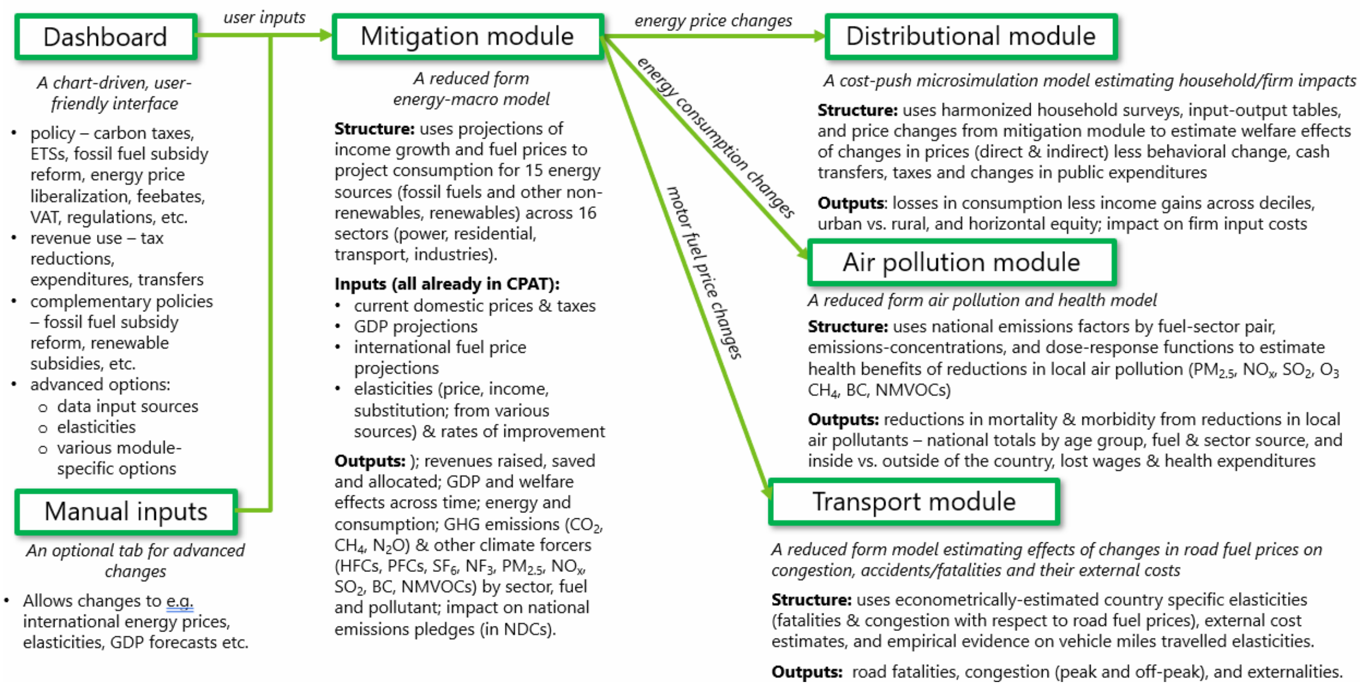
[25] For the mitigation section, see: https://www.edx.org/course/macroeconomics-of-climate-change-mitigation-strategies.

2. Overview of CPAT Structure

CPAT is a spreadsheet-based ‘model of models’ with four key components (‘modules’; Figure 2):

1. **Mitigation module** – a reduced-form macro-energy model for estimating impacts of climate mitigation policies on energy consumption, prices, GHGs, local air pollutants, revenues, GDP, and welfare;
2. **Distribution module** – a cost-push microsimulation model for estimating impacts of energy and non-energy price changes on industries and households (by consumption decile and region), net of revenues used (‘revenue recycling’) for public investment, transfers, or personal income tax (PIT) cuts;
3. **Air pollution module** – a reduced-form air pollution and health model for estimating impacts on premature deaths and disease from local air pollutants like fine particles (e.g., $PM_{2.5}$) and ozone; and
4. **Transport module** – a reduced-form model for estimating the impacts of motor fuel price changes on congestion and road accidents/fatalities as well as their external costs.

Figure 2. Overview of CPAT Structure

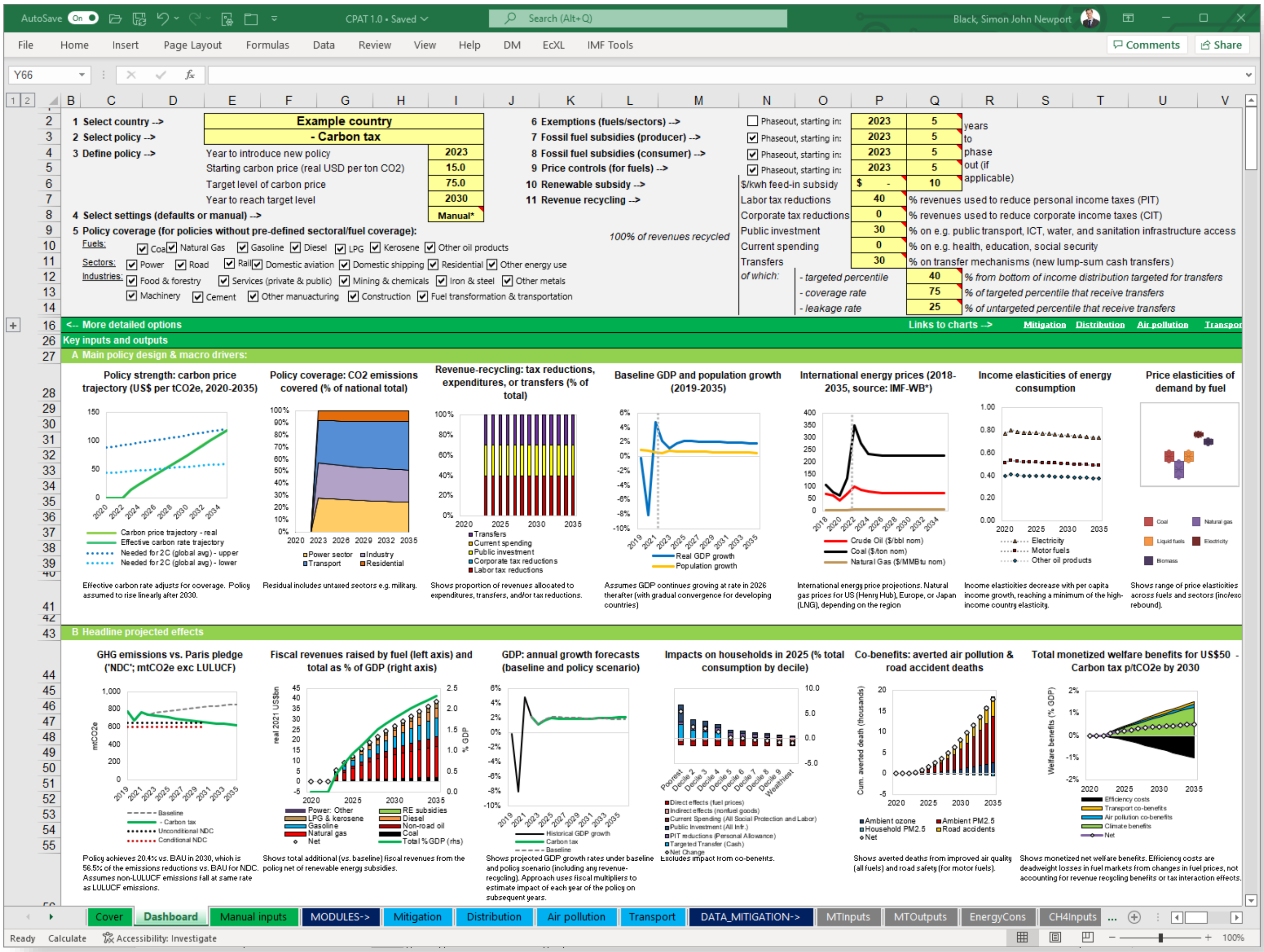


Source: IMF and WB staff.

The user interacts primarily with the ‘Dashboard’ without the need to input external data (Figure 3). The Dashboard is a chart-driven, user-friendly interface. The user selects the country of interest, mitigation ‘policy scenario’ (e.g., carbon or energy taxes), the strength/coverage of the policy (across fuels and sectors), and complementary policies (e.g., fossil fuel subsidy reform, energy price liberalization, and feed-in subsidies for renewables). Any revenues raised or saved can be allocated to tax reductions, current spending, public investment, or transfers. Key parameters (e.g., price and income elasticities) can be customized by the user. Within seconds, the user sees the main results in six key charts[26] and over 100 more detailed charts. CPAT does not require any external data to function for the countries covered, but users can input such data (e.g., on domestic energy prices) in the ‘Manual Inputs’ tab.

[26] Key charts include: GHG emissions projections compared with NDCs in the BAU and policy scenarios, net changes in fiscal revenues by fuel source in the policy scenario, GDP impacts by component, incidence impacts on household consumption deciles, averted premature deaths from improvements in air quality and road safety, and net changes in welfare by component (abatement costs less monetized externality benefits from climate and health/transport co-benefits).

Figure 3. CPAT Main Interface ('Dashboard')



Source: IMF and WB staff.

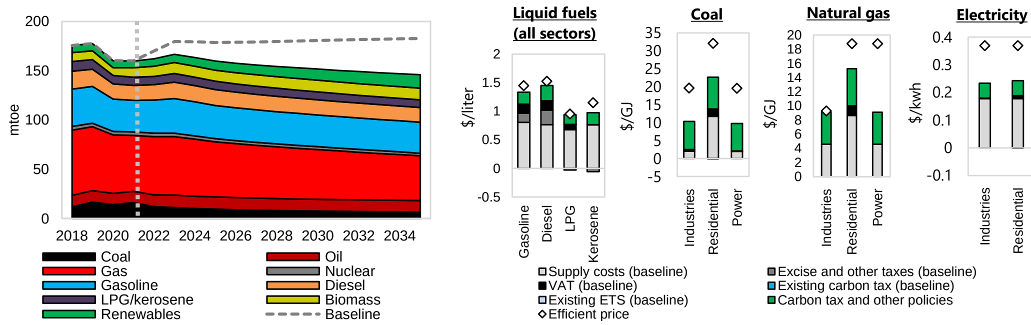
The mitigation module, which is the core of CPAT, is a reduced-form macro-energy model. It provides, on a country-by-country basis, projections of energy demand and supply, prices, CO_2 and other GHG emissions by fuel and sector, revenues, GDP, abatement costs and welfare impacts, as well as several other metrics. These are estimated under the BAU scenario and for many different mitigation policies, including: carbon taxes, ETSs, fossil fuel subsidy reform, fuel/electricity taxes, energy price liberalization, renewables subsidies and feed-in tariffs, VAT harmonization, energy efficiency and emission rate standards, feebates, methane fees, and combinations of these policies ('policy mixes').

Figure 4 shows example outputs from the mitigation module. There are around 50 other charts available to the user with outputs including: energy demand and prices (including gaps to socially optimal price levels[27]); national emissions and electricity capacity, investment and generation by energy source; impacts on trade of energy goods; sectoral decarbonization targets (in NDCs); impacts on revenues from changes in taxes and subsidies on fuels, electricity, and renewables; impacts on GDP over time and by policy change (taxes, expenditures, investments, or transfers); GHG emissions by sector, gas, and fuel; and, finally, energy-related CO_2 emissions by sector, industry, and fuel. Additionally, key inputs are displayed graphically, including growth forecasts, global energy prices, and price and income elasticities.

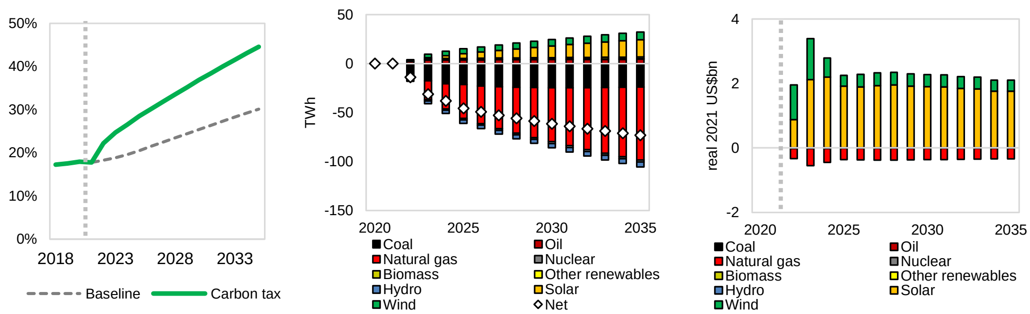
[27] See Parry and others (2021c)

Figure 4. Example Outputs from CPAT Mitigation Module
(for US$50 Carbon Price/ton CO_2e by 2030, Unspecified Country)

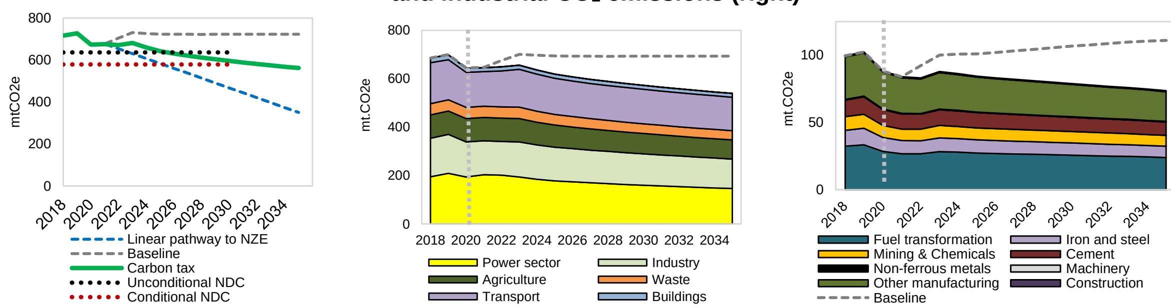
Panel A. Energy – Modelled total energy demand by fuel (left) and impacts on 2030 energy prices (right)



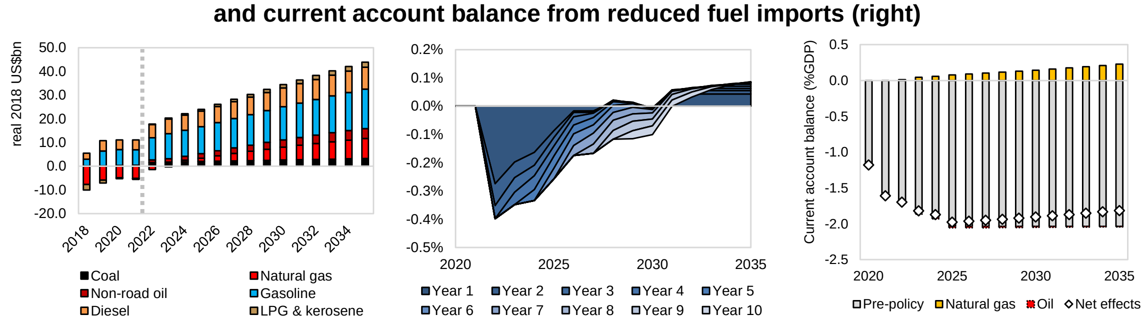
Panel B. Electricity – renewable shares of power generation (left), changes in generation by source (middle), and changes in annual investment in power capacity (right)



Panel C. Emissions – GHGs vs. targets (left), GHG by sector (middle), and industrial CO_2 emissions (right)



Panel D. Economic – revenues raised by fuel (left), net impacts on GDP levels by reform year (middle) and current account balance from reduced fuel imports (right)

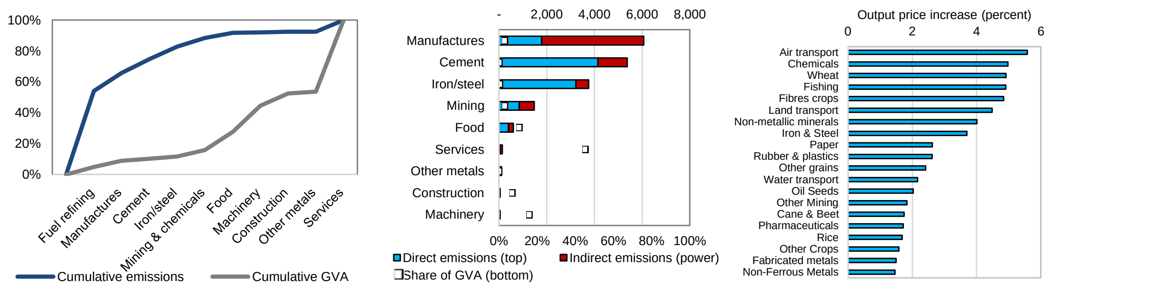


Source: IMF staff using CPAT.

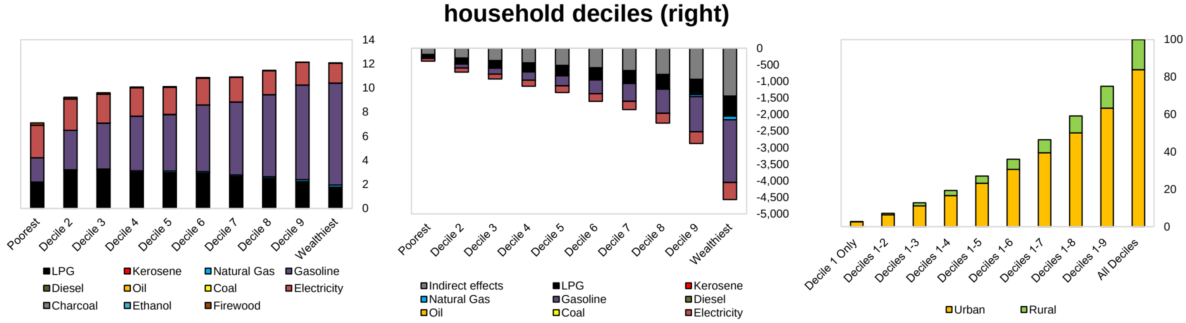
The distribution module estimates incidence impacts from climate mitigation policy on industries (for many sectors) and households (across and within deciles). Changes in energy prices affect industry input and, hence, production costs. Impacts are estimated for 59 non-energy sectors (e.g., steel, cement, chemicals). For households, detailed information on budget shares is used to estimate effects across consumption deciles, both ‘direct’ (from changes in energy prices) and ‘indirect’ (from changes in prices of non-energy goods and services), and on net (accounting for revenue recycling). Effects are estimated at the decile level and between urban and rural regions for a growing set of countries.[28]

Figure 5. Example Outputs from CPAT Distribution Module

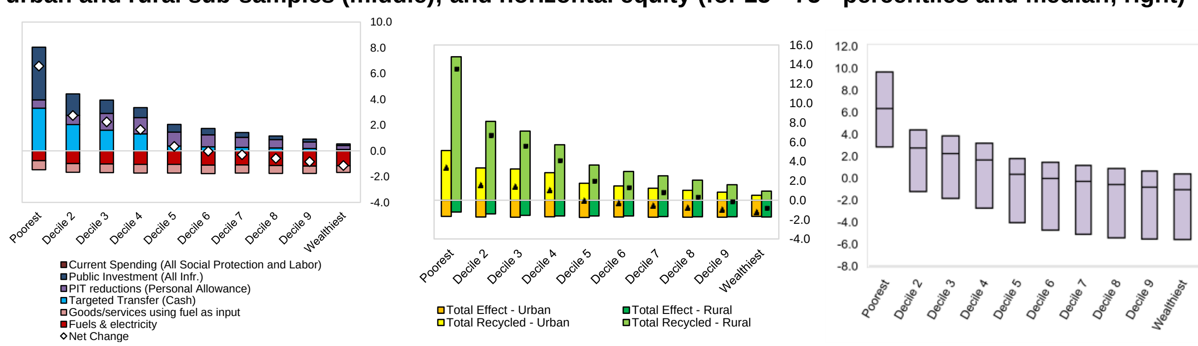
Panel A. Industry impacts – cumulative CO_2 emissions and gross value added (GVA) (left), emissions intensity of production (tCO_2 per \$m GVA; middle), and price (cost) impacts on 20 of 59 most affected industries (right)



Panel B. Households – BAU energy consumption (percent of total by decile; left), initial impact on household consumption (absolute LCU by decile; middle), and cumulative revenues needed to compensate given household deciles (right)



Panel C. Net household incidence – mean consumption effect (percent pre-policy consumption; left), between urban and rural sub-samples (middle); and horizontal equity (for 25th-75th percentiles and median; right)



Source: IMF staff using CPAT. Note: LCU = local currency units.

Figure 5 illustrates some example outputs from the distribution module. These include impacts on industry, direct and indirect effects on households from changes in energy and other goods’/services’

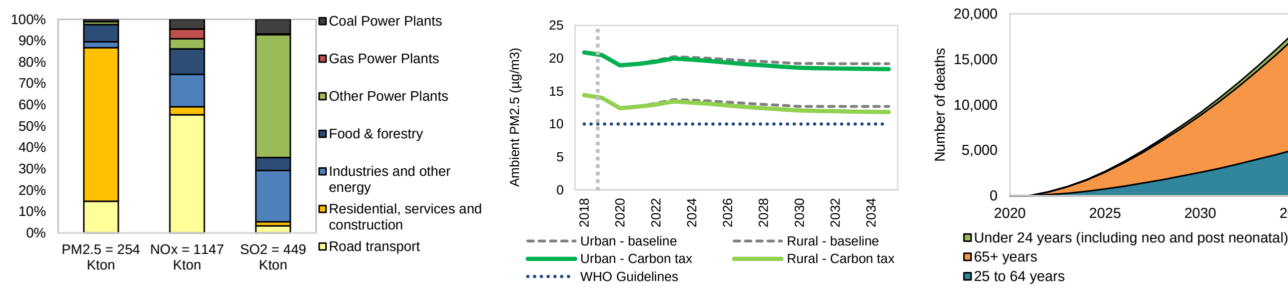
[28] Industry analysis requires input-output (IO) tables, which have been harmonized for 120 countries to date. Household analysis requires household budget surveys (HBSs), which have been harmonized for over 65 countries to date.

prices, and net incidence impacts (accounting for 'revenue recycling' i.e., use of revenues raised or saved for, e.g., PIT cuts or cash transfers). Around 25 figures are available, including: impacts on industrial input and output prices (for 59 sectors); composition of household consumption of energy and non-energy goods/services by decile; absolute consumption effects before and after revenue recycling by decile and between urban and rural sub-samples; cumulative share of revenues required for compensating given household deciles (e.g., bottom 10 percent); changes in inequality and horizontal equity (median, 25th, and 75th-percentile impacts within each decile for all, urban, and rural households).

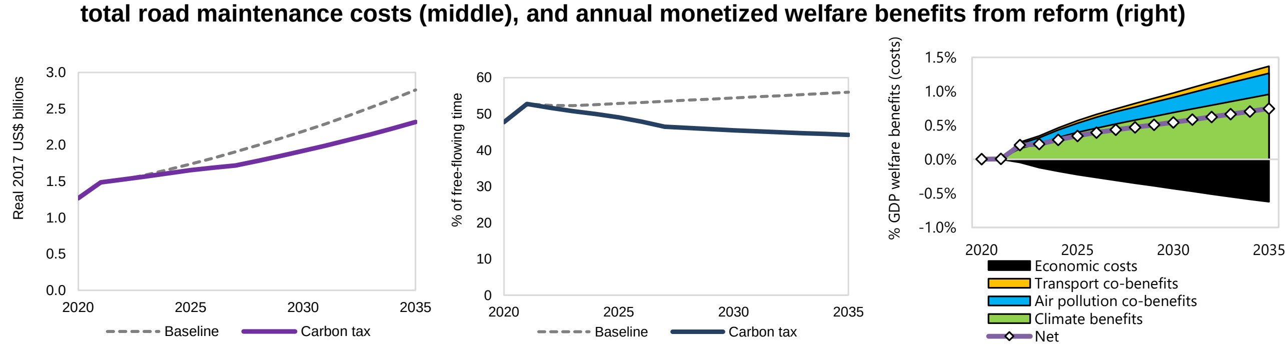
The two remaining modules (air pollution and transport) capture the welfare spillovers from climate policy on health, congestion, and road safety (known as 'development co-benefits'). Fossil fuel combustion creates emissions of local air pollutants like fine particulate matter ($PM_{2.5}$, produced directly and indirectly from atmospheric reactions) and low-lying ozone (O_3). These contribute to the 4.5 million premature deaths (in 2019) from outdoor air pollution and many more instances of diseases like asthma and stroke (IHME 2020). Cuts in fuel combustion can, therefore, help improve human health. The air pollution module estimates these benefits by disease, age group, location, and source using several methods. Lastly, increases in road fuel prices tend to cut road accidents, congestion, and their associated external costs which, alongside other road sector impacts, are estimated by the transport module.

Figure 6. Example Outputs from CPAT Air Pollution and Transport Modules (for US$50 Carbon Price/ton CO_2e by 2030, Unspecified Country)

Panel A. Air Pollution – Baseline emissions of local air pollution by source and pollutant (left), changes in local air pollution concentrations (middle), and cumulative avoided deaths by age (right)



Panel B. Transport & Welfare – Congestion as a share of travel time (left), total road maintenance costs (middle), and annual monetized welfare benefits from reform (right)



Source: IMF staff using CPAT.

Example outputs from the air pollution and transport modules are shown in Figure 6. These include baseline emissions of $PM_{2.5}$, NO_x and SO_2 by source, impacts on urban and rural $PM_{2.5}$ concentrations, avoided deaths by age group, changes in congestion and road maintenance costs, and finally total net welfare impacts from the policy. There are around 50 other charts available, including: relative risk of diseases; emissions factors; baseline and changes in deaths by type (indoor, outdoor, ozone), sector, disease, and age group (infants, children, working age, and 65+); changes in morbidity (years lived with disease and disability adjusted-life years); GDP losses due to air pollution; avoided lost wages; savings in health expenditures by payee (government, private, and donors); and changes in external costs from reduced congestion, road accidents, and maintenance. These and other data on co-benefits can help governments fully appraise social, health, and welfare changes of different climate mitigation policies.

3. Mitigation Module

This section describes the mitigation module, including how the BAU and policy scenarios are modelled and impacts on key metrics of interest (energy demand, emissions, revenues, GDP, and welfare). For more technical details, see Annex I – Technical Details: Mitigation Module.

Modeling the BAU and Policy Scenario

To estimate the impacts of climate policy on metrics of interest, the mitigation module contains a 'business-as-usual' (BAU) and policy scenario. In both cases energy consumption is split into 15 fuels and electricity sources produced or consumed by 17 sectors:

- Energy sources – coal, natural gas, gasoline, diesel, kerosene, liquified petroleum gas (LPG), jet fuel, other oil products, electricity, wind, solar, hydro, other renewables, nuclear, and biomass.
- Sectors – consistent with UNFCCC, these include power generation, transport (road, rail, shipping, and aviation, including domestic and international), buildings (residential, food & forestry, public & private services), industries (mining & chemicals, iron & steel, other metals, machinery, cement, other manufacturing, construction, fuel transformation & transport), other energy use and non-energy use.

These are projected forward from a base of recently observed fuel and electricity consumption using:

- GDP projections (see Annex I: GDP for details);
- Domestic energy prices and projections of future international energy prices (See Annex I: Energy prices and International and domestic energy price projections);
- Assumptions about the income elasticity of demand and own-price elasticity of demand for fuels and electricity (see Annex I: Own-price elasticities of demand for energy products consumed by households and firms and Income elasticities of energy demand); and
- Assumptions on rates of technological change due to exogenous efficiency improvements in fuel-consuming assets and in the cost and productivity of key low-carbon technologies like renewables.

For more information on the energy sector see Energy Demand, Energy Supply and Energy Sector: Key Assumptions sections in Appendix I.

The model is parameterized using data compiled from various sources by country and sector. Energy demand and production data is from the International Energy Agency (IEA 2022a), Enerdata (2022), and other sources. GDP projections are from the latest IMF forecasts.[29] Data on energy taxes, subsidies, and prices by energy product has been compiled from publicly available and IMF sources, with inputs from proprietary and third-party sources.[30] International energy prices are projected forward using an average of WB and IMF projections for coal, oil, and natural gas prices, which are then used to project domestic prices using empirical estimates of pass-through by country.[31] Elasticities are calibrated to empirical evidence through an extensive literature review (Annex I) and yield estimates that are broadly in line with the mid-range of BAU emissions and policy scenario responsiveness implied by other models.

Given the power sector's importance for decarbonization, CPAT contains two power supply models. Climate mitigation requires decarbonizing electricity generation while electrifying end-uses of energy across sectors and for all countries. Power supply is estimated using two models: an elasticity-based model and a hybrid technology-explicit ('technoeconomic') model. The former uses elasticities which

[29] Based on the IMF's World Economic Outlook for initial years, followed by assumptions of steady growth, including gradual convergence for developing countries to developed country GDP growth rates (estimated using the IMF-ENV CGE model): no country can sustain negative or high GDP growth in the long run. However, it should be noted these effects exclude the negative growth effects of global climate change. Adjustments in emissions projections are also made to account for partially permanent structural shifts in the economy caused by the pandemic.

[30] See Parry and others (2021c).

[31] These are empirically estimated and bucketed by the CPAT team, though are unity for most fuels and sectors. Pass-through rates less than 1 are assumed to imply that the government imposes price controls (e.g., government-imposed fuel pricing formulas) through subsidization. See Annex for further elaboration. For an alternative approach for projecting pass-through rates for motor fuels, see Kpodar and Abdallah (2016)

estimate changes in the generation mix in response to relative price changes (from fuel and other costs). The latter incorporates an explicit stock of power generation assets with an investment and dispatch decision. Projections of levelized costs of electricity (LCOE) for generation are combined with assumptions on retirement rates, capacity factors, physical or economic limitations, and the increasing need for storage. The system makes forward-looking investments in new capacity while dispatching existing assets. Electricity prices vary for industrial and residential users, which determines electricity demand.

In the BAU, current fuel taxes/subsidies and carbon pricing are held constant in real terms. This assumes countries do not add to or strengthen existing mitigation policies.[32] For fuels, it is assumed that international energy supply is able to meet demand with exogenous international fuel prices.

In the policy scenario, the user selects from a broad range of mitigation policies, including:

- Price-based policies – such as carbon pricing (carbon taxes and ETSs[33]), fuel and electricity taxes, fossil fuel subsidy reform, energy market reform such as price liberalization[34], VAT reform.
- Renewable subsidies – feed-in tariffs (equivalent to a renewable production tax credit) for renewable power generation (to accelerate adoption of wind and solar).
- Regulatory policies – emission rate standards, energy efficiency standards, and their 'fee and rebate' analogues ('feebates'; taxes on carbon intensive goods or production used to fund subsidies on low-carbon intensity goods or production).
- Policy mixes – the above can be combined, e.g., a carbon tax with fossil fuel subsidy reform, energy price liberalization, VAT harmonization and renewable subsidies.

Impacts of Policies on Energy, Emissions, and Achievement of NDCs

The impacts of price-based mitigation policies such as carbon pricing on fuel use and emissions depend on: (i) impacts on energy prices, and (ii) the price responsiveness of fuels by sector. In the industry, buildings, and transport sectors, price changes impact demand for fuels by incentivizing shifts to more efficient and cleaner technologies along with direct reductions in fuel demand (e.g., from reduced driving or reduced demand for steel). In the power sector, investments in new generation (to replace retirements or meet rising electricity demand) shift from fuels like coal and natural gas plants towards low-carbon technologies like solar and wind[35], subject to physical or economic limitations on scaleup alongside an increasing need for electricity storage. Dispatch depends based on the generation mix, with fuel-based power becoming more expensive, partially raising electricity prices and dampening power demand and, hence, overall generation. See Annex I: Impacts of Policies and Targets for more details.

Non-price policies such as regulations are modelled using a shadow pricing approach. Regulatory policies such as emission rates or energy efficiency standards enhance the efficiency of energy-consuming capital goods but generally have limited impacts on consumer prices. Given the large plethora of design choices for regulations, they are modelled similarly to price-based policies through a shadow price. This impacts the efficiency of energy-consuming capital goods without impacting direct demand for energy like a price-based policy would. This allows for comparisons of policies on energy consumption and emissions.

Total GHGs and local air pollutants are estimated via emissions factors by fuel, country, and sector. These are provided by the International Institute for Applied Systems Analysis (IIASA)[36] for:

[32] This is comparable with the IPCC's 'current policies' scenario, which is SSP2-4.5 (Shared Socioeconomic Pathway; see IPCC 2022). The closest IEA equivalent is the Stated Policies Scenario – see IEA (2022a).

[33] Behavioral responses are assumed to be slightly lower for ETSs compared with carbon taxes as evidence suggests that the price uncertainty of permits impedes their relative cost effectiveness – see e.g., Aldy and Armitage (2020).

[34] Energy market reforms such as automatic pricing schemes reinforce the effectiveness of price-based policies such as ETSs in electricity markets. However, these need not be precursors to pricing – see Acworth and others (2020) for discussion.

[35] In default settings, hydroelectric capacity is assumed to be fixed as it is assumed that countries have already exhausted these opportunities. Nuclear is allowed to be phased-up (with a lag) in countries which already have fission reactors.

[36] Based on the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model; see Wagner and others (2020). Emissions factors for local air pollutants in the future are estimated using an average of current and planned policies.

- Greenhouse gases – the 'Kyoto gases' of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and F-gases (HFCs, PFCs, SF_6, NF_3). These are included in UNFCCC inventories except for NF_3.[37]
- Fine particulate matter ($PM_{2.5}$) and ozone (O_3) – includes PM sources from black carbon (BC), organic carbon (OC), volatile organic compounds (VOCs), carbon monoxide (CO), nitrous oxide (NO_x), and sulphur dioxide (SO_2). Ozone is formed when local air pollutants react in the presence of sunlight. $PM_{2.5}$ and, to a smaller degree, ozone cause millions of premature deaths globally, and are estimated by the air pollution module. They can also have localized warming or cooling effects, which are also estimated.[38]

CPAT's mitigation module also includes non-energy emissions from: land use, land use change and forestry (LULUCF); agriculture; industrial processes; waste; and other sources. Historical GHGs are compiled by IMF staff using data from the UNFCCC, the Emissions Database for Global Atmospheric Research (EDGAR),[39] the Food and Agriculture Organization of the United Nations (FAO), and national sources.[40] LULUCF emissions are assumed to decline steadily for countries with positive emissions and be flat for countries with negative emissions.[41] Industrial process emissions scale with energy-CO_2. Agricultural CO_2 emissions scale with population and per-capita income while waste emissions scale with population. Methane emissions from agriculture, waste, and extractives are estimated using country-specific emissions factors, assuming autonomous technical change, GDP growth and, in the policy scenario, marginal abatement cost curves. Under default settings, non-CO_2, non-methane GHGs are assumed to change at the same rate as energy emissions.[42] See Annex I: Non-Energy Sectors for details.

Using this approach, mitigation pledges in NDCs can be estimated and compared. The mitigation module converts all quantifiable, economy-wide mitigation pledges into percent reductions vs. BAU in 2030 defined in terms of GHGs excluding LULUCF.[43,44] This allows for estimation of whether a country's target is likely to be met under the policy scenario (or baseline in the case of non-binding pledges) as well as comparisons of mitigation ambition across countries. The latest forecasts for these NDCs, alongside emissions projections from CPAT, can be found on the IMF's Climate Indicators Dashboard.[45]

Impacts on Revenues, GDP, and Welfare

Revenues are estimated by comparing total revenue from fuel and electricity taxes, net of outlays on fuel or renewable subsidies, in the BAU versus the policy scenario. This captures both increases

[37] Global warming potentials to convert non-CO_2 GHGs into CO_2-equivalent are based on 100-year Global Warming Potentials (GWP100), though Global Temperature Potentials (GTPs) are also available. GWP is a measure of the heat absorbed over a period, whereas GTP is a measure of the temperature change at the end of that period, relative to CO_2. Total energy-related emissions are adjusted to match what countries submit to UNFCCC (where available) by adjusting emission factors. Local air pollutants such as particulate matter (PM) are not covered by UNFCCC but can still have warming or cooling effects (see footnote below), and hence are also included in CPAT for informational purposes.

[38] The impacts of local air pollutants on local warming and cooling generally counteract each other in many cases. For example, SO_2 has a local cooling effect while BC has a local warming effect. Hence, reducing combustion of fuels that emit PM sources will have a local warming effect (via SO_2) and cooling effect (via BC). In most cases, net effects are small compared with reducing GHGs from cutting fossil fuel combustion, though this varies at the subnational level.

[39] EDGAR is a joint project of the European Commission Joint Research Center (EC-JRC) and the Netherlands Environmental Assessment Agency (PBL). See https://edgar.jrc.ec.europa.eu/methodology.

[40] See IMF Climate Change Indicators Dashboard, available at: https://climatedata.imf.org/

[41] Per the latest Coupled Model Intercomparison Project (CMIP6) exercise used by IPCC, most scenarios assume emissions from LULUCF will be flat between 2020 and 2040 – see IIASA (2021).

[42] This is equivalent to turning a carbon tax into a GHG tax assuming a similar responsiveness of non-energy consuming sectors to that of energy consuming sectors. Estimating impacts of non-energy sector responses is, however, difficult, and this assumption does not currently yield impacts on revenues, prices, and GDP, and can also be switched off.

[43] LULUCF emissions are commonly excluded from assessments of NDCs. This is due, in part, to uncertainties in land-based emissions of agriculture amounting to 4 to 5.5 gtCO2 or roughly 7 to 10 percent of total annual global GHGs (Grassi and others, 2018). Recent work has made progress on reconciling differences (Schwingshackl and others, 2022).

[44] Sectoral parts of NDCs (e.g., renewables shares) are excluded from target emissions levels. This is because a country with an unambitious NDC that achieves an ambitious sectoral target could increase emissions in other sectors and still achieve its target, hence economy-wide components of NDCs are the most important from a mitigation perspective.

[45] See https://climatedata.imf.org/

in revenues from new fuel taxes as well as cuts in revenues from base erosion for pre-existing energy taxes. Leaving aside base erosion, revenue-raising policies include carbon taxes, ETSs with auctioned allowances, increases in energy excises, VAT harmonization, and reductions in fossil fuel subsidies. Revenue-reducing policies include expenditures (e.g., on renewable subsidies), green public investments, and most regulations. Regulations, like tradable emission rate standards, are revenue-neutral while feebates can be revenue-raising, neutral or reducing, depending on their design. Users can recycle revenues towards increases in public investment, (targeted) transfers, current spending, cuts in personal income and/or corporate taxes, or a mix thereof. For revenue-reducing reforms, users can choose tax bases to raise taxes from to ensure overall revenue-neutrality. See Revenue section in Annex I for details.

GDP impacts are estimated for each country and year.[46] Fiscal multipliers are common macroeconomic parameters, usually stated in terms of the impact on output in the years following the reform.[47] These are extracted from external models and empirical studies and used to estimate the deviation from projections. Policies such as carbon pricing impact GDP over time depending notably on how revenues are recycled.[48] Reductions in PIT and increases in public investment tend to be more supportive to GDP (either minimizing GDP losses or yielding a net gain, one version of the 'double dividend' hypothesis[49]) than increasing transfers or current government expenditures.[50] Net effects also vary over time, though in aggregate both ex ante and ex post empirical evidence suggests that GDP impacts of mitigation policies are small (slightly positive or negative) or ambiguous in sign.[51] GDP impacts can have second-order effects on energy consumption and emissions, for example with small increases (decreases) if GDP rises (falls), though these rebound effects are not material in practice.[52] See GDP impacts in Annex I for details.

The impacts of policy reforms on welfare are estimated in several ways. Welfare effects are estimated applying long-established formulas from the public finance literature[53] and reflect integrals under marginal abatement cost schedules as well as efficiency effects due to compounding/offsetting pre-existing distortions from fuel taxes/subsidies. At present, (to be conservative) CPAT does not capture additional welfare effects from revenue recycling and other interactions with the broader fiscal system (see Box A1.1 in Annex I). The domestic benefits from reduced environmental costs of fuel use ('development co-benefits') such as reductions in premature mortality from local air pollution, traffic accidents, and congestion are estimated separately by the air pollution and transport modules—external costs from these factors are used in welfare calculations.[54] See Welfare or efficiency costs and net economic benefits section in Annex I for more details.

[46] The climate mitigation policy impacts on GDP (due to higher energy prices) described here are consistent with the industry/sector-level cost increase simulations of the CPAT distribution module (see discussion in Section 4 and relevant Annexes below), which are based on the same set of energy price changes generated by the CPAT mitigation module.

[47] For a discussion of fiscal multipliers' use and estimation, see Batini and others (2014).

[48] The supply of fossil fuels is assumed to be flat in CPAT. In effect, when examining the policies of individual countries, it is assumed that their mitigation policies do not significantly affect global prices and supply of fuels.

[49] For an extensive discussion of the double dividend hypothesis regarding the effects of environmental tax reforms such as carbon pricing as it relates to GDP, welfare, and employment, refer to Heine and Black (2019).

[50] The design of PIT reductions and country context, such as prevalence of informality, affect growth impacts of reform. Some design nuances, such as reducing differences in compliance between labor and capital taxes, are not captured.

[51] Multipliers are from the WB's Macro-Fiscal Model (MFMod; Burns and others 2019) and Schoder (2022). GDP effects are uncertain and vary with country and policy reform. The ex-ante modelling literature tends to find that revenue-neutral environmental tax reforms raise employment but have ambiguous impacts on GDP and welfare (Heine and Black 2019). However, empirical studies have found little evidence of a negative impact from carbon pricing policies on GDP or employment – see, for example, Bretscher and Grieg (2020) and Metcalf and Stock (2020).

[52] Because the impacts of mitigation policies on GDP tend to be small (see above footnote), the rebound effects also tend to be small. This rebound through GDP should not be confused with the separate rebound of policy-induced energy efficiency, which would result in a small offsetting increase in energy demand due to lower marginal costs of energy.

[53] See Harberger (1964).

[54] Based on IMF methodologies in the default case (Parry and others 2014, 2015, 2021c), though other approaches to estimating air pollution mortality effects are available in the tool.

Box 1. Planned Improvements in CPAT Mitigation Module

Several enhancements are presently envisaged for future iterations of the mitigation module.

In implementing mitigation policies, countries are increasingly adopting a sectoral approach (Black and others, 2022a). The tool would benefit from more granular representation of energy-consuming sectors, their technologies, and sectoral policies. Models with dynamic capital turnover have been developed separately for transport and buildings and will be incorporated in future versions. These models include a dynamic capital stock which allows for better modelling of sectoral policies, such as a tightening of emission rate standards (for new or existing vehicles and buildings) and green industrial policies such as subsidization of newer technologies.[55] This can also allow for quantification of the spillover impact of technology policies on costs due to learning curve effects[56] and the impact of capital vintages on optimal mitigation strategies.[57] Other, more refined, industry- and activity-specific sectoral models, such as for industrial sectors like steel, chemicals, and cement, alongside agriculture, and forestry, are planned.

Additionally, economic impacts, policy coverage, and international linkages will be enhanced. GDP and international trade effects will be better modelled, notably for industrial sectors and for fossil fuel exporting countries. Incorporation of planned policies – for example for nuclear in power and efficiency in buildings – will enhance the representation of governments' existing plans. The representation of the production structure tables will be improved through use of the IMF's forthcoming Multi-Analytical Regional Input-Output (IMF-MARIO) database. Lastly, welfare effects estimates could be improved through incorporation of distortions in the fiscal system (Parry and others, 1999) as well as informality and other relevant channels (Bento and others, 2018; Heine and Black, 2019).

Lastly, it is envisioned that CPAT will increasingly allow for linkages with external models, either to give outputs to or consider inputs from. These models could include, for example, macroeconometric models such as the Macro-Fiscal Model (MFMOD; Burns and others 2019), computable general equilibrium (CGE) models like IMF's ENVISAGE (IMF-ENV; Chateau and others 2022), sectoral models such as the Future Technology Transformations models (FTT; Mercure 2012, Mercure and others 2018, Knobloch and others 2019, Vercoulen and others 2019), the IMF's Fiscal Analysis of Resource Industries model (FARI; Luca and Mesa Puyo 2016), and others.

Caveats

There are several caveats to CPAT's mitigation module (though some of these will be addressed in future improvements to CPAT – see Box 1). First, the module abstracts from the possibility of:

- **Non-linear responses to large policy changes**. For example, a large increase in emissions prices could facilitate a rapid adoption of carbon capture and storage (CCS) or direct air capture technologies, though the future costs of these technologies are uncertain.[58] Additionally, the model does not capture the impacts of widescale technological change which may be induced by climate policy and could imply higher price elasticities (alongside more positive impacts on GDP[59])
- **Learning-by-doing spillovers in low-carbon technologies***.* Renewables have sharp learning curves, with the costs of solar declining 90 percent between 2010 and 2020, for example.[60] The model includes assumptions on learning rates for key technologies, but these are not endogenized at present (policy in one country is not assumed to impact global learning rates) and may be too conservative (implying lower BAU emissions and potentially higher price responsiveness).

[55] For a discussion of green industrial policies, see Hallegatte and others (2013).

[56] Wright's law relates the impact of cumulative production of technologies with the change in unit costs: as firms get better at producing technologies (e.g., via learning-by-doing) average total costs decline – refer to Grubb and others (2021).

[57] The need for rapid decarbonization and the long-lived nature of some energy-consuming capital goods as buildings (in addition to market failures) justifies additional policy effort in these sectors – see Vogt-Schilb and others (2018).

[58] Cost projections for CCS, while highly speculative, are around $75 to $175 per ton CO_2e (see Gillingham and others 2018, Keith and others 2019).

[59] See Heine and Black (2019).

[60] See Way and others (2021).

- **Feedback from fuels markets.** The possibility of upward-sloping fuel supply curves[61] and other changes in international fuel prices that might result from simultaneous climate or energy price reform in large countries would impact results. Parameter values are, however, chosen such that the results from the model are broadly consistent with those of more detailed energy models that, to varying degrees, account for these types of factors (see Annex I).

Other caveats for the initial iteration of the mitigation module ('CPAT 1.0') include:

- **International linkages across countries are limited.**[62] CPAT accounts for changes in fuel and electricity imports and exports (e.g., due to decarbonization) and changes in trade are accounted for in GDP estimates, but the coverage of traded products is limited. This prevents explicit analysis of the implications of border carbon adjustments (BCAs), for example, which are receiving increasing attention, though additions are planned.

- **Impacts from policy changes on GDP are simplified.** GDP impacts are estimated as described above to account for general equilibrium effects of climate policy changes (e.g., from changes in employment, balances of payments, monetary factors, etc.) to adjust the forecasted growth path. In general, this is a reasonable approach.[63] However, it should be noted that fiscal multipliers are currently aggregated at the region and income-group level, while country-specific circumstances (e.g., debt distress) are not currently included.[64] Economic effects also do not account for interactions between climate mitigation policies and distortions in the economy created by the broader fiscal system, which can reduce policy costs (e.g., through recycling carbon pricing revenues in broader tax reductions). GDP impacts from changes in informality, induced technical change, or local air pollution (for example on productivity) are also not included but could be substantive.[65]

- **Sectors are de-coupled at present but will become increasingly integrated in future updates (Box 1).** Global decarbonization requires cutting emissions in power generation while electrifying end-uses of energy, creating inter-sectoral linkages. For example, electric vehicles will add modestly to electricity demand while hydrogen is likely to become more readily available for decarbonizing industry (though the share of hydrogen in industry energy consumption is likely to remain small this decade). As a result, future updates will add interactions between electrified sectors and power demand.

- **Lastly, price elasticities used may be too high in the short term and too low in the long term.** CPAT assumes the impacts of prices on energy use are fully realized within one year.[66] This may somewhat overstate responsiveness in the short-term, as firms and households take time to adjust, but it is a reasonable approximation as the focus is on policies that are phased in over several years. [67] Also, there is initial evidence that price elasticities used may be too low in the long run. Empirical elasticity studies tend to examine responses to price changes induced by market fluctuations. However, policy-induced price changes may elicit responses that can be much larger than market-induced changes (e.g., due to higher salience and expected permanence of tax-induced changes).[68] Users can, however, adjust price elasticities.

[61] The assumption of flat fuel supply curves is reasonable for countries that are price-takers in international fuel markets and for coal over the longer run (given its vast reserves). Large producers may, however, have some market power in international markets for oil and natural gas, implying that changes in domestic supply may have some domestic price effects.

[62] The bulk of empirical evidence thus far suggests that leakage effects (alongside competitiveness, see below) from climate mitigation policies are small or statistically insignificant (Eskander and Fankhauser 2023). However, these may be due to low prices and exemptions, while some empirical studies find larger effects (see e.g., Wingender and Misch 2021). Simulation-based studies find high or low impacts depending on parameters.

[63] See, e.g., IMF Staff Guidance Note (IMF 2022h).

[64] However, improvements to the representation of GDP in CPAT to account for country-specific circumstances are in development. Simulation and empirical studies indicate that GDP effects of mitigation policies remain quite uncertain, though current evidence suggests they are small or, in some cases, positive. See footnote 51.

[65] For a more detailed discussion, see Heine and Black (2019).

[66] In substance, this only affects the energy intensity component of elasticities, accounting for roughly half of the responsiveness. Additionally, one of the power sector supply models in CPAT accounts for short-term limits on new investment in response to mitigation policy. Lastly, dynamic models of capital turnover for the transport and building sectors have been developed to distinguish policies that only affect new (as opposed to new and existing) capital.

[67] Previous versions included short- and long-term elasticities but results were not significantly affected by this distinction.

[68] See, for example, Li and others (2014), Anderrson (2019) and Moore and others (2021).

4. Distribution Module

Income inequality and poverty are increasingly important in discussions of climate mitigation policies. Given the need for a 'just transition' as recognized by Parties to the UNFCCC, distributional impacts of climate policy have become more relevant to policymakers. Public acceptability can be strongly driven by the level of fairness of reforms, notably their impact on (low-income) households. In addition, policymakers are increasingly interested in the impact of policies on exporting or import-competing firms, especially those in energy intensive, trade exposed (EITE) sectors. The impact of policy-induced price changes and use ('recycling') of revenues raised or saved on households and industries are crucial design considerations. This section describes the distribution module (for technical details, see Annex II – Technical Details: Distribution Module).

The Distributional Impact of Climate Mitigation Policies

Changes in energy prices from climate mitigation policies can have a regressive or progressive effect on households, depending on the country. Broadly, in low- and middle-income countries, carbon pricing policies (before revenue recycling) tend to be moderately progressive, since grid access and ownership of energy-intensive goods, such as cars and appliances, tend to be more concentrated towards the top of the income distribution (Mercer-Blackman and others, 2022). In high-income countries, changes in energy prices tend to be regressive because, for example, ownership of energy-intensive goods tends to be broader than in developing countries (Heine and Black 2019, Ari and others, 2022).

However, for all countries, revenues raised or saved can make reforms pro-poor and equity-enhancing overall. Climate mitigation policies can have negative absolute impacts on the vulnerable, even when incidence effects are progressive (affecting wealthy households more as a share of pre-policy consumption). In the case of revenue-raising policies such as carbon pricing and fossil fuel subsidy reform, revenues can be used to compensate (or more than compensate) vulnerable households. Cash transfers, social safety nets, and investments in education and health can disproportionately benefit the poor. This could help countries make progress towards achieving Sustainable Development Goals (SDGs) and is especially relevant for lower-income countries where domestic revenue mobilization is constrained by informality. By contrast, non-pricing mitigation policies, such as regulations, do not have a first-order impact on energy prices, and hence do not affect households in the same way pricing policies do. However, non-pricing policies also do not raise revenues (and erodes the base for existing energy taxes). In such cases, it may be more difficult to influence the net distributional effect of the policy (e.g., via revenue recycling).

Additionally, countries are increasingly interested in the impact of climate mitigation policies on firms. As countries scale up mitigation policies, policymakers may be concerned about impacts on firms that compete in international markets (exporting or import-competing firms), such as those operating in EITE industries like steel, cement, and chemicals. Governments may fear these industries will lose market share through an increase in input costs relative to firms in other countries. Firms could also move production overseas, partially offsetting the policy impact on global emissions ('carbon leakage'). These fears may be overstated given empirical evidence,[69] but impacts on EITE firms remain a concern for policymakers nonetheless.[70]

CPAT's distribution module estimates impacts of climate mitigation policies on 59 non-energy economic sectors across 120 countries. Impacts are quantified as changes in firms' input costs and output prices, presented by industry/sector and the share of each industry/sector in gross value added (GVA), total output, household demand, and exports. This can aid policymakers in estimating impacts on firms, especially in EITE industries, and can inform countries considering policies to protect firms such as BCAs (Parry and others 2021c) or, ideally, an international carbon price floor (Parry and others 2021a).

[69] On competitiveness, a meta-study of 103 publications finds that strict but flexible environmental policies increase competitiveness of firms and countries overall (a 'strong version' of the 'Porter hypothesis'; see Cohen and Tubb 2018). A systematic review finds that two thirds of 54 studies show no negative impacts on firms from taxes and ETSs (Peñasco and others 2021). On leakage, most empirical studies so far find statistically insignificant effects – see footnote above.

[70] For example, evidence suggests that a country with a larger share of industry in GDP is less likely to adopt a carbon price, which could be due to policymaker fears of losses in competitiveness (Dolphin and others 2020).

Impacts before Revenue Recycling and Responses

The CPAT distribution module quantifies impacts of mitigation policies on firms and households. It models the impact of rising energy prices on firm production costs and on household consumption of energy goods ('direct effects') and non-energy goods and services ('indirect effects'). For households, net impacts are estimated accounting for revenue recycling through PIT reductions, transfers, and public expenditures. The module also allows for the estimation of these impacts across (vertical distribution) and within (horizontal distribution) consumption deciles, and between households in rural and urban areas.

The distribution module follows a standard, cost-push microsimulation approach, common in the literature.[71] This combines HBSs (scaled such that total HBS-estimated consumption matches household consumption in national accounts) with input-output (IO) table data. This allows for estimation of impacts of changes in prices (from the mitigation module) on the input costs of affected industries, increases in expenditures for households, and losses in consumer surplus ('burdens') of households.[72] The user can vary several assumptions and policy design, such as whether and how to target poorer households for compensation. The module also adjusts for changing energy product budget shares over time, improvements in the energy efficiency of production, and for behavioral responses to higher energy/non-energy prices.

Data on household budget shares is obtained from HBSs for, so far, over 65 countries. Data is aggregated into CPAT-compatible good/service categories[73] and households are grouped into population-weighted, per-capita consumption deciles. Budget shares are computed by dividing total expenditure on each good/service by each household's total consumption expenditure across all goods/services. Sector-specific price increases for each energy source and sector from the policy scenario are obtained from the mitigation module. This allows for estimation of increases in expenditures and losses in consumer surplus from changes in the price of energy and other goods/services.

For 'direct' and 'indirect' effects, price increases for energy and other goods/services (due to higher energy input prices) are calculated within the module. In the default case, it is assumed that price changes are fully passed forward onto consumer prices (i.e., flat/perfectly elastic energy supply curves). Energy price changes are obtained from the mitigation module and affect households' consumption of fuels and electricity (direct effect; see Equation (16) in Annex II). Non-energy sector price increases are obtained as the sum-product of: i) each sector's energy intensity (see Annex II for details); and ii) the change in energy prices induced by the policy. Sectoral energy intensities are derived from global IO tables[74] that are mapped to CPAT non-fuel consumption good/service categories mentioned above. Summing the estimates across all non-fuel goods/services yields the increase in expenditures (e.g., on food, housing, etc.; indirect effect).

Impacts on expenditures can be converted into welfare-equivalent measures, i.e. losses in consumer surplus ('burdens'). While households can face losses in consumption from increased prices (not accounting for the benefits of revenue recycling), they also incur additional losses in utility from the presence of a tax wedge. Total welfare-equivalent losses ('burdens') which include deadweight losses are estimated in CPAT (see Annex II for more details).

[71] See, for example, Fabrizio and others (2016).

[72] Consumer surplus here is defined as the portion of the Marshallian aggregate surplus that is captured by consumers, with the remainder captured by firms. Marshallian aggregate surplus can be thought of as the utility gained from consumption of a good less its production costs. Graphically, consumer surplus is the area between the demand curve and equilibrium prices for goods. See Mas-Collell (1995, p.326). Burdens are measured by losses in consumer surplus, which include: i) extra household expenditures on goods due to their higher prices (a first-order effect); and ii) the value to households of forgone consumption induced by price changes, net of reduced spending (a second-order effect).

[73] To facilitate relative cross-country comparability of results, CPAT uses a standardized classification of goods and services across all countries, distinguishing among 8 energy goods (coal, electricity, natural gas, oil, gasoline, diesel, kerosene, LPG) and 14 non-energy goods/services (appliances, chemicals, clothing, communications, education, food, health services, housing, other, paper, pharmaceuticals, recreation and tourism, transportation equipment, public transportation).

[74] At present, from the Global Trade Analysis Project (GTAP)-10 database which includes data for year 2014 across 65 sectors. These cover the following five fossil fuels: coal, electricity, oil, natural gas, and petroleum products. See: https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx. IO tables will be updated to incorporate any periodic updates to the GTAP database vintages (e.g., from GTAP-10 to GTAP-11), or alternatively may shift to the IMF's forthcoming MARIO database.

The above approach also allows for estimation of impacts on industries. This analysis is particularly important when examining international competitiveness impacts (e.g., for EITE industries).[75] Cost increases are calculated as simple sectoral averages or weighted/ranked by sectoral output, exports, final household demand, and gross value-added (GVA). The user can make a distinction between input (i.e., producer) and output (i.e., final, consumer) price changes by applying imperfect pass-through coefficients from the literature.[76] Results are available for 59 sectors as well as 8 aggregated CPAT sectors.

However, by not considering effects of revenue recycling or behavioral responses, these first-order impacts do not capture welfare effects. Households and firms respond to price changes by adjusting consumption bundles and input mixes, both of which reduce net impacts on households. Additionally, revenues raised or saved from the reform can be recycled, with varying impacts across households.

Impacts after Revenue Recycling and Responses

The distribution module accounts for behavioral responses in two ways. The first approach adjusts for 'behavioral and structural change' in the economy. It does this by uniformly scaling downwards impacts across deciles by the ratio of revenues raised per the mitigation module to revenues raised based on the HBS data. This scaling implicitly adjusts the estimated effects from changes in the carbon intensity of the economy implied by the (older) IO tables and that of the (newer) energy consumption balances. The second approach adjusts for behavioral responses by considering decile and product-specific price elasticities of demand. These elasticities are derived from country-level data (by income group) sourced from the United States Department of Agriculture (USDA)[77] and applied assuming households behave according to a constant elasticity of substitution (CES) utility function. See Annex II for technical details.

Use of revenues raised or saved is important for comprehensively evaluating the distributional impacts of climate mitigation policies. Revenue recycling through cash transfers, PIT reductions, and creating or scaling-up existing social assistance programs can make reforms that appear initially regressive (i.e., relatively more burdensome for the bottom of the income distribution), in fact, both progressive (enhancing the equity of the fiscal system) and pro-poor (raising the absolute welfare of the poorest deciles).

Four 'modes' of revenue recycling can be simulated. i) new or existing targeted transfers (for which the user can decide the targeted percentiles and targeting inefficiency); ii) transfers towards public investment in infrastructure; iii) scaling up an existing social protection scheme; and iv) reducing effective PIT liabilities. Infrastructure transfers are assumed to target parts of the income distribution without initial access to clean water, electricity, sanitation, information technologies, or public transport. Increases in current spending are assumed to benefit households proportionally to existing social protection schemes (e.g., social assistance, insurance, or in-kind benefits). Revenue recycling via PIT reforms can take the form of proportional or lump-sum reductions in household consumption decile-specific PIT liabilities or to exempt deciles entirely. Finally, transfer schemes are also available for population segments below international poverty lines . Lastly, the module estimates the share of revenues required to compensate parts of the income distribution (e.g., the bottom two deciles). See Annex II for technical details.

Both (negative) consumption effects as well as (positive) revenue recycling effects are expressed as shares of pre-policy consumption and in absolute (monetary) per-capita terms. This is done at the household decile level and separately for rural and urban sub-samples. For vertical distribution impact outputs (between groups), the user can further choose between decile mean and median HBS data inputs. Horizontal impacts (within groups) are estimated for the 25th and 75th percentile within each decile.

[75] In this case, the assumption of flat supply curves (i.e., households bearing the entire incidence of the policy) may not be valid: domestic firms competing in international markets may not be able to pass forward cost increases onto consumers.

[76] Users can use coefficients from Ganapati and others (2020), Neuhoff and Ritz (2019) and Abdallah and others (2020) – refer to Annex II for further details.

[77] See: https://data.ers.usda.gov/reports.aspx?ID=17825

Caveats

The distribution module is subject to several limitations:[78]

- **Changes in economic structure may not be fully accounted for.** In calculating the indirect effects of policy, the share of each sector in total consumption and output remains constant over time (they are, nonetheless, scaled in gross terms with GDP). However, the relative production structure is likely to change, especially with longer time horizons and more aggressive mitigation policies.
- **The impacts of imperfect pass-through of changes in input costs to output costs are only partly accounted for.** The module assumes, by default, full pass-through of producer price increases onto consumers or, equivalently, flat supply curves at the domestic market level (see Annex II for options to relax this assumption). However, higher energy prices could be passed backwards into lower producer prices (e.g., assuming upward-sloping supply curves). If this impacts profits, some of the incidence could be borne by firm owners (via lower capital returns) or workers (via lower wages).
- **Various other channels, not commonly accounted for in cost-push microsimulation models, can affect incidence estimates (including regressivity or progressivity).** To the extent that fossil fuel-intensive industries are capital-intensive, climate policies may increase returns to labor. This could, in turn, mean that (wealthier) households deriving a larger share of their income from capital could be disproportionately hurt by climate mitigation policies (relative to poorer households that derive most of their income from wages). Additionally, to the extent that poorer households live in more polluted areas (within cities), they may benefit relatively more from reductions in local air pollution induced by climate policies. More research on these channels is required to ascertain their relative importance.

5. Development Co-Benefits Modules: Air Pollution and Transport

Climate mitigation policies have broad impacts beyond carbon emissions, including ancillary benefits (‘co-benefits’) for human health and welfare. CPAT contains two modules for estimating two of the key co-benefits of climate policy: i) health improvements from reductions in local air pollution; and, ii) welfare benefits from reductions in vehicle use in response to higher road fuel prices, via reduced congestion, accidents, and road maintenance costs.[79] These modules are briefly described below. Further details can be found in Annex III.[80] For more details on the development co-benefits modules, see Annex III – Technical Details: Co-Benefits Modules (Air Pollution & Transport).

Air pollution co-benefits module

Burning fossil fuels and biomass emits pollutants that damage human health. Outdoor (‘ambient’) air pollution mortality and morbidity occur through people inhaling $PM_{2.5}$ (particulate matter with diameter up to 2.5 micrometers, fine enough to penetrate the lungs and bloodstream) and low-lying ozone (O_3). $PM_{2.5}$ is emitted directly from fuel combustion or formed indirectly from atmospheric reactions involving precursors (SO_2, N_2O, BC, other organic matter, and ammonia (NH_3)) emitted from burning fuels. Low-lying ozone can inflame and damage airways and aggravate lungs. Ozone is formed indirectly through atmospheric reactions among precursors (volatile organic compounds (VOCs), CH_4, CO, N_2O, and/or SO_2).

The associated social and health costs are substantial. The Global Burden of Disease (GBD) reported 4.5 million deaths from outdoor air pollution in 2019, with 92 and 8 percent due to $PM_{2.5}$ and ozone, respectively, and 60 percent from burning of fossil fuels. Indoor air pollution caused a further 2.3 million

[78] For a discussion of general limitations of cost-push distributional analyses, see Heine and Black (2019) and Shang (2023).

[79] While there are other co-benefits from reducing fuel use, such as improved energy security, they are generally smaller, more difficult to quantify, and better addressed through other policies (see NRC 2010, Chapter 2).

[80] Further details, including on options not commonly used in the IMF but available to users can be found in more in-depth documentation available on the WB’s accompanying website (linked to from www.imf.org/cpat).

deaths.[81] As with climate damages, outdoor air pollution is principally an externality, since individuals and firms do not consider the risks to others from emissions released when fossil fuels are combusted.

CPAT quantifies the mortality, morbidity, and economic costs of local health damages stemming from fossil fuel use for each country in four main steps. First, local air pollutant emissions ($PM_{2.5}$, SO_2, N_2O, BC, CO, VOCs and CH_4) are estimated using energy use by fuel, sector, and scenario, as described in the mitigation module section above. Second, emissions of pollutants are translated into concentrations of $PM_{2.5}$ and ozone and population exposure. There are two main approaches used for this in CPAT: intake fractions and the TM5-FASST approach, which are then averaged.[82]

The intake fraction method estimates the portion of $PM_{2.5}$ that, on average, is inhaled by exposed populations. This approach was first used in Parry and others (2014) and has since been refined in collaboration with the WB. For coal, natural gas, and oil power plants, intake fractions are derived using spatial data on power plant locations matched to granular data on population density at different distances from each plant (within and across borders) and regression coefficients describing the fraction of emissions ingested given population density at different distances.[83] For vehicle, building, industry, and other emissions (released generally closer to ground level), intake fractions were extrapolated nationwide from a database of (ground-level) intake fractions for over 3,000 urban areas. Intake fractions tend to be higher in densely populated areas and lower where emission sources are coastally located and a large portion of emissions dissipate over the ocean without harming local populations.[84]

The TM5-FASST is an emulator of the full TM5-Chemical Transport Model (CTM) that relates emissions from a source to air quality ($PM_{2.5}$ and ozone) at that and other locations ('receptors'). The results in CPAT are based on this 'source-receptor' approach downscaled at the country level and augmented by local source apportionment studies.[85] The air quality modelling approach is more sophisticated than the intake fraction approach in that it accounts for local meteorological and topographical factors influencing ambient pollution concentrations. On the other hand, air quality modelling is less granular for the application of fossil-fuel related sources like power plants, implying less precision in estimating populations potentially exposed to fossil fuel-related pollution.

The third step is to map population exposure to $PM_{2.5}$ and low-lying ozone to health burdens. This is done using, by age class, baseline mortality rates for illnesses whose prevalence is increased by air pollution exposure and exposure-response curves from the 2019 GBD study. For $PM_{2.5}$, CPAT assesses jointly the impacts of outdoor and indoor air pollution (although it does not explicitly model policies that affect indoor air pollution). Outputs include mortality and disability-adjusted life years (DALYs).

Fourth, the two approaches are averaged and changes in mortality risk valued. The monetization of mortality risks is contentious, but necessary to factor health risks into estimates of efficient energy prices and determine tradeoffs among policies. The approach draws on an OECD (2012) meta-analysis of several hundred studies on health risk valuations, which (after updating for inflation and income growth) implies a value of around US$4.6 million per death avoided for 2020 in the average OECD country. This is extrapolated to other countries based on incomes relative to the OECD and an assumed mortality risk elasticity.[86] Lost wages from morbidity are included, but account for a small portion of total costs.

[81] See IHME (2020).

[82] Other methods are also available in CPAT, including machine learning-based methods.

[83] Data is available for 164 countries. Intake fractions for other countries are inferred from comparable countries in each region.

[84] The intake fraction is converted to a pollution concentration by scaling by the breathing rate.

[85] TM5-FASST (the TMF-FAst Scenario Screening Tool, see Van Dingenen and others, 2018) is based on a linearized version of TM5, a detailed atmospheric chemistry model. The original source-receptor matrices in TM5-FASST are separated into 56 regions which are then downscaled to country-specific matrices and supplemented with local source apportionment studies which estimate the contribution of sources such as fossil fuels to baseline concentrations.

[86] See Parry and others (2014), and Table 7 in Viscusi and Masterman (2017). Extrapolations are based on purchasing power parity, which more accurately reflects people's willingness to pay for risk reductions out of income. Mortality valuations may also differ across countries with differences e.g. in life expectancy, health, economic and social support and so on, though effects of these factors are not well understood (Robinson and others 2019). Some argue for an income elasticity above 1 to reflect lower income households' relatively higher utility from spending (e.g., as more spending is on essentials) but Viscusi and Masterman (2017) fail to reject an elasticity of 1. CPAT allows for adjustments to the income elasticity.

Caveats

The air pollution co-benefits estimates are subject to several caveats.

- **Temporal and geographical scope***.* CPAT provides an estimate of annual health co-benefits averaged over the population. In reality, there can be significant variation in pollution exposure during both the course of the year and across urban and rural areas. Information on this temporal and spatial variation could inform the design of fine-tuned air emissions fees.
- **Uncertainty in the relationship between emissions, concentrations, and health impacts***.* While there is consensus that $PM_{2.5}$ and ozone impact health significantly, there is uncertainty on the exact relationship between the emissions of pollutants and concentrations of $PM_{2.5}$ and ozone, and between concentrations and the incidence of specific illnesses. While the above describes the default approach, CPAT provides five methods in total to estimate this relationship, all of which have been cross-checked against more complex air quality models, allowing for sensitivity analysis.

Road transport co-benefits module

Climate policies can impact human welfare by affecting congestion, road accidents, and road damage. By raising the costs of gasoline and diesel, climate policies can reduce vehicle kilometers travelled (VKT), by incentivizing public transport, carpooling, trip chaining, and reducing overall travel demand. This has impacts on economically costly congestion, as well as road accidents and wear and tear on roads. Some of these costs are borne by individuals while others are borne by others. External costs are relevant for assessing the welfare impacts of climate policies and the extent to which these policies are in countries' own domestic interests before counting global climate benefits.[87] Policymakers may also be interested in other metrics like total travel delays and road fatalities, not least because they are easier to explain. As discussed below, CPAT estimates all of these metrics, with further details provided in Annex III.

Congestion is a major problem in cities across the world. Congestion is measured as the time lost due to the actual travel speed being slower than a 'free-flowing' speed (i.e., the speed under no congestion), mostly in urban areas. Despite a marked reduction in congestion in 2020-2021 from changes in urban mobility and work patterns due to the COVID-19 pandemic, congestion rose in 2022 in most cities.[88]

In the baseline, CPAT forecasts congestion delays using historic congestion growth rates, adjusted for GDP and population growth, and in the policy scenario using elasticity estimates. The baseline forecast for congestion is calculated using the last available year of data (from TomTom) projected forward using historic congestion growth rates, adjusted for GDP and population growth. As congestion applies mainly to urban, working-age populations, we calculate the time lost in traffic due to congestion for the VKT of this share of the population. The policy forecast calculates how much time would be lost in congestion when fuel prices change due to new policies, using an econometrically estimated fuel price elasticity.

Road accidents cause about 1.3 million deaths per year (94 percent in low- and middle-income countries[89]) and various other costs including injuries, medical burdens, and property damage. CPAT provides estimates of total road accident fatalities in the baseline scenario and how they are affected by mitigation policies using empirical estimates of the link between road fuel prices and road fatalities. The accident fatality baseline forecast (in the BAU) is projected forward using the latest available data from external data sources (OECD, IRF, and United Nations Economic Commission for Europe (UNECE)) as well as average past growth rates adjusted for GDP and population growth. This baseline forecast is compared to a policy forecast (if fuel was taxed more heavily), calculated using the abovementioned fuel price elasticities and the fuel price change due to the policy.

CPAT also provides estimates of the marginal external costs of congestion and accidents and associated welfare benefits. The marginal external cost of congestion is the impact of motorists adding to

[87] Parry and others (2015). Total external costs from all road externalities are estimated at almost $1 trillion in 2020, with two-thirds coming from congestion alone (Parry and others 2021c).

[88] See https://www.tomtom.com/newsroom/explainers-and-insights/the-most-congested-cities-in-the-world-2022/

[89] See https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries

congestion and costly delays for other road users. Changes in total external costs are the product of the reduction in fuel induced by the policy and the marginal external costs per liter. It is estimated by multiplying average travel delays per VKT by: (i) the relationship between marginal and average travel delays based on traffic speed-flow curves; (ii) vehicle occupancy (averaging over cars and buses); (iii) people's value of travel time (VOT, assumed to be 60 percent of the nationwide average market wage in 2020); (iv) fuel economy (to convert costs per VKT into costs per liter of fuel); and (v) the portion of the fuel demand elasticity that comes from reduced driving (and therefore affects congestion) versus the portion that comes from improved fuel economy/shifting to EVs (which does not affect congestion).[90]

CPAT also includes estimates of marginal accident externalities per liter of fuel use. A portion of accident costs are commonly viewed as internal to drivers (e.g., own-driver injuries) while other costs are external (e.g., injury risks to pedestrians, elevated risks to occupants of other vehicles from multi-vehicle collisions, and property and medical costs borne by third parties). Accident externalities per liter are measured[91] by apportioning country-level data on traffic fatalities into external versus internal risks, monetizing them using the above approach for mortality valuation, extrapolating estimates of other components of external costs from several country case studies to other countries, and dividing by fuel use, scaling by the portion of the fuel price elasticity that reflects reduced driving.

The road transport module also estimates the impacts of changes in VKT on road damage as measured by road maintenance costs. The baseline forecast of road maintenance costs is projected from the latest available data (from the International Road Federation (IRF)) and for future years using average historic road maintenance cost growth and an empirically derived relationship between road maintenance costs and GDP and population growth. Externalities are assumed to be 50 percent of total maintenance costs, with the other half attributed to weather and natural deterioration. The entire externality is attributed to diesel consumption, since damage is caused by high axle-weight vehicles that primarily use diesel as a fuel (again, scaled by the driving portion of the diesel fuel price elasticity).

Finally, VKT itself may be a metric of interest. The base value for VKT comes from the IRF, while changes in subsequent years are a function of average VKT growth, GDP and population growth as well as changes in fuel prices (both due to international commodity fluctuations and changes in prices following climate mitigation policy adoption).These relationships are estimated econometrically (at the country level, where data is available) and differentiate between short- and long-run responses, as some responses materialize more slowly (e.g., purchases of fuel-efficient vehicles and moving closer to population centers).

Caveats

The road transport co-benefits estimates are subject to some caveats:

- **Fuel price elasticity estimates are assumed to be causal.** The estimated relationship between changes in fuel prices and VKT may not be well-identified. In the empirical approach, country and year fixed effects control for unobserved heterogeneity across countries and global trends. However, endogeneity cannot be entirely ruled out (e.g., there may be unobserved, time-varying factors correlated with both the explanatory variable and the error term).[92] Results are, nonetheless, consistent with more detailed, country-level studies from the relevant literature.
- **Data quality may affect the results.** Changes in key indicators, such as VKT and accidents, are estimated econometrically and, thus, impacted by the quality of historical data. Where data is not available for a given country, IMF region and income group averages are used to infer the relationships between GDP growth, population, price responsiveness, and driving-related indicators.
- **The impacts of electrification of road transport (through plug-in and hybrid electric vehicles, EVs) are not currently modelled explicitly.** EVs also create driving-related externalities, but

[90] Further adjustments are made to account for the relatively weaker responsiveness of driving on congested roads (which is dominated by commuting) to fuel taxes than driving on free-flowing roads and the share of buses and trucks in the vehicle fleet (which contribute more to congestion per VKT). See Parry and others (2014), Ch. 5.

[91] See Parry and others (2014), Ch 5.

[92] For a discussion of these issues, see Angrist and Pischke (2009).

consume less or no gasoline or diesel, so a tax on petroleum products would not effectively price externalities from EVs. However, future iterations of CPAT are expected to address this (see Box 1).

- **Proxy taxes on driving-related externalities in the future may be preferable to road fuel duties for pricing road externalities.** Driving-related externalities are more effectively taxed through policies that directly target external costs (e.g., per-VKT charges related to prevailing congestion). CPAT currently allows for taxes imposed on an energy consumption basis. Future updates of the model could include targeted policies, which are becoming more viable with better technologies.

6. Conclusion

Stabilizing the global climate requires climate mitigation policy reforms across countries. Global GHG emissions must be cut by 25 to 50 percent this decade to be on track with limiting warming to well below 2ºC, and ideally 1.5ºC, above pre-industrial levels. Such a rate of decarbonization is unprecedented, necessitating new policies and a strengthening of existing policies. This includes carbon pricing (carbon taxes and ETSs), fossil fuel subsidy reform, energy market reform and price liberalization, renewable energy subsidies, feebates, green public investments, regulations, VAT harmonization, and mixes thereof. Analytical tools are required to help policymakers design and assess reform packages which accelerate decarbonization (including in high-cost sectors) while supporting other government objectives.

CPAT can help policymakers in over 200 countries assess, design, and implement reforms that cut GHG emissions while supporting other objectives. CPAT allows for the rapid quantification of impacts of climate mitigation policies. It can therefore help governments identify, design, communicate, and implement reforms that decarbonize economies while supporting other objectives such as growth, poverty alleviation, equity, environmental quality, and energy access. While some tradeoffs are inevitable in policymaking, a variety of welfare-enhancing climate mitigation reforms are both desirable and feasible across countries.

To ensure reforms are durable, policymakers should also consider political economy factors. While CPAT can inform assessments of the likely political acceptability of reform, for example by quantifying incidence impacts on industries and households, varying national contexts can mean varying preferences for mitigation policy design.[93,94] As such, separate qualitative analyses (e.g., public opinion surveys) can help inform both the design of policies and in the communication of their benefits.[95]

Reforms should include measures to facilitate a 'just transition' and 'deep decarbonization'. To ensure that vulnerable households are not left behind, policies focused on retraining, relocation, and financial support for displaced workers (e.g., in coal mining regions) will be needed. In addition, broader policies beyond CPAT's scope are needed to facilitate abatement in the highest-cost sectors, notably to address technology-related market failures.[96] Such policies could include prizes, support for basic research, and advance market commitments for newer, more expensive technologies.

The need for policy packages that accelerate decarbonization has never been so universal nor urgent. By making CPAT available to policymakers, its developers at the IMF and WB hope to help countries implement needed climate mitigation policies, stabilize the climate, and achieve a more sustainable future.

[93] There is a relationship among the policies of different countries: evidence suggests policies can diffuse across borders. Linsenmeier and others (2022b) find that one country implementing mitigation policies increases the chances that other countries adopt the same policies. The emissions reductions from such positive policy externalities may be even larger than domestic emissions reductions. However, types of mitigation policies may vary in the extent they cross international borders (Dolphin and Pollitt 2021) and within countries over time (Linsenmeier and others 2022a).

[94] Some reform designs appear generalizable from a political acceptability standpoint. For example, evidence suggests that public attitudes towards carbon taxes and fossil fuel subsidy removal are similar and that recycling revenues through per-capita transfers, labor tax reductions, or expenditures towards climate mitigation or adaptation projects can enhance acceptability (Carattini and others 2019, Harring and others 2023).

[95] Effective communications and transparency are important for reform durability – see Coady and others (2018).

[96] For example, firms are unable to internalize all the benefits of innovation, due to learning-by-doing spillovers. As a result, private investment in low-carbon R&D may lie below what is socially optimal, even in the presence of a robust carbon price.

Annex I – Technical Details: Mitigation Module

This technical annex describes the structure of the mitigation module, including how the energy sector is modelled (key sectors, sources, assumptions), the impact of policies (on emissions, revenues, welfare, NDCs and other metrics), and additional emissions sources from non-energy sectors.

Overview of Model Structure

CPAT's mitigation module uses production-based emissions inventories in that it does not include emissions embodied in imported goods.[97] Consistent with this, the model distinguishes five main energy-consuming sectors:[98]

1. *Power*, including generation of both electricity and district heating and distribution, which supplies demand by households and firms;
2. *Industry*, which distinguishes eight subsectors – mining & chemicals, iron & steel, non-ferrous metals, machinery, cement, construction, fuel transformation & transportation, and other manufacturing;[99]
3. *Transportation*, which distinguishes road (mostly gasoline from light-duty vehicles and diesel from heavy-duty vehicles), rail (mostly from diesel engines), domestic aviation (mostly jet fuel), and domestic shipping (mostly diesel and fuel oil);[100]
4. *Buildings*, which includes primary (i.e., excluding electricity) energy demand in residential, industrial, and commercial buildings, and (public and private) services—energy use in agriculture and forestry are also included in this sector, as is common in national GHG inventories; and
5. *Other,* which represents miscellaneous emissions not captured in other sectors.

CPAT also distinguishes the following energy sources:

1. *Fossil fuels***,** including coal, natural gas, gasoline, road diesel, liquified petroleum gas (LPG), kerosene, (domestic) jet fuel, and 'other oil products' (e.g., used in power generation, petrochemicals, home heating), and;
2. *Electricity***,** as generated by fossil fuels, renewables (including wind, solar, hydro, and biomass, and other renewables such as geothermal; either as part of the grid or off-grid such as small-scale solar photovoltaic in residential or industrial uses), nuclear energy, and imported from or exported to other countries.

Electricity is measured in kilowatt hours (kWh), coal and natural gas in gigajoules (GJ), road fuels in liters (l), oil and other oil products in barrels of oil (bbl), and other energy sources such as nuclear and other renewables in kilotons of oil equivalent (ktoe).

The following subsections discuss energy demand, supply, and market equilibrium in CPAT.

[97] This is customary globally: countries' emissions inventories submitted to the UNFCCC as well as climate mitigation pledges in NDCs are defined in terms of production-based inventories that exclude emissions embodied in exported or imported goods. See https://di.unfccc.int/detailed_data_by_party.

[98] CPAT also includes a couple of small, miscellaneous fuel use categories which are presumed to be excluded from carbon pricing or other mitigation instruments including residuals from energy consumption balances (e.g., for military purposes) and non-energy use of fuels (e.g., oil for lubrication). Baseline emissions from these sectors increase at the same rate as for industry.

[99] These sectors broadly represent the most energy-intensive, trade exposed (EITE) sectors, and hence are of particular interest to policymakers.

[100] International aviation and maritime fuels are included as distinct international sectors in CPAT (and hence are included in global emissions projections), rather than included in country data as responsibility for developing strategies to mitigate their emissions lies with the international bodies regulating these sectors.

Energy Demand

General Formulation

In the general equation used for all energy demand in CPAT, the final demand for a particular energy source in a period *t* is determined by:

$$(1) \qquad E_t = \left(\frac{u_t}{u_{t-1}} \cdot \frac{h_t}{h_{t-1}}\right) \cdot E_{t-1}; \qquad \frac{u_t}{u_{t-1}} = \left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \left(\frac{h_t \cdot p_t}{h_{t-1} \cdot p_{t-1}}\right)^{\eta^u}; \qquad \frac{h_t}{h_{t-1}} = (1+\alpha)^{-1} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h}$$

where:

E_t is demand at time t for a specific energy good in a particular sector

u_t is usage of energy-consuming capital goods

h_t is the energy consumption rate of capital goods, the inverse of energy efficiency

v_t is the income elasticity for the energy good which may change over time (see below)

p_t is the price for energy in the sector

η^u is the price elasticity of demand for the usage of energy-consuming capital goods

$\eta^h < 1$ is the price elasticity of the energy consumption rate

$0 < \alpha < 1$ is the autonomous rate of efficiency improvements for energy-consuming capital goods (e.g., reflecting the gradual replacement of older, less efficient capital with newer, more efficient capital).

The formulation in (1) allows CPAT to model policies targeted at energy consumption rates, while only data on energy consumption (not its decomposition into energy-using capital and energy consumption per unit of capital) is needed to implement (1).

In the industrial sector, E_t is use of coal, natural gas, oil and electricity and is implicitly equal to the product of industrial output and the corresponding fuel and electricity use per unit of output. In the transport sector, E_t is use of vehicles in the road, aviation, and shipping sectors of fuels in liters or electricity in kWh, implicitly equal to vehicle kilometers travelled (VKT) times liters of fuel or electricity use per VKT. Finally, in the buildings sector, E_t is use of oil, natural gas, other fuels, or electricity for space heating/cooling, lighting, and cooking and is implicitly equal to the building stock times fuel or electricity use per unit of time.

From equation (1), use of energy-consuming goods increases with GDP according to the income elasticity of demand, which is generally less than unity (implying demand increases by less than in proportion to GDP). Use of energy-consuming goods also declines with proportionate changes in unit energy costs according to the usage elasticity, where the unit cost is the product of the energy consumption rate and the energy price. The energy consumption rate declines over time with exogenous improvements in energy efficiency and with increases in energy prices according to the energy consumption rate elasticity.
Price elasticities are constant within and across periods (which is a common assumption).

To provide more intuition on energy price elasticities, equation (1) can be rewritten with respect to the energy price in period *t*[101] to give the following expression:

[101] From formula (1): $E_t = \left(\frac{u_t}{u_{t-1}} \cdot \frac{h_t}{h_{t-1}}\right) \cdot E_{t-1}; \frac{u_t}{u_{t-1}} = \left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \left(\frac{h_t \cdot p_t}{h_{t-1} \cdot p_{t-1}}\right)^{\eta^u}; \frac{h_t}{h_{t-1}} = (1+\alpha)^{-1} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h}$

$$E_t = E_{t-1}^{Ei}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \left(\frac{h_t \cdot p_t}{h_{t-1} \cdot p_{t-1}}\right)^{\eta^u} \cdot (1+\alpha)^{-1} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h}$$

$$E_t = E_{t-1}^{Ei}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \frac{1}{(1+\alpha)} \cdot \left(\frac{1}{(1+\alpha)} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h}\right)^{\eta^u} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h+\eta^u}$$

$$E_t = E_{t-1}^{Ei}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \left(\frac{1}{(1+\alpha)}\right)^{1+\eta^u} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h\eta^u} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h+\eta^u}$$

$$E_t = E_{t-1}^{Ei}\left(\frac{GDP_t}{GDP_{t-1}}\right)^{v_t} \cdot \left(\frac{1}{(1+\alpha)}\right)^{1+\eta^u} \cdot \left(\frac{p_t}{p_{t-1}}\right)^{\eta^h+\eta^u+\eta^h\eta^u}$$

Hence the total own price elasticity $\eta^E = \eta^h + \eta^u + \eta^h\eta^u$

$$(2) \qquad \eta^E = \underbrace{\eta^u}_{(-)} + \underbrace{\eta^h}_{(-)} + \underbrace{\eta^h \eta^u}_{(+)}$$

where η^E is the total own price elasticity of demand for energy. This elasticity has three components, interpreted below in the context of transport:

- η^u is the elasticity of VKT with respect to the fuel price, for a given fuel consumption rate—this reflects both reductions in VKT per vehicle and reductions in the vehicle stock;
- η^h is the elasticity of the fuel consumption rate with respect to the fuel price—this reflects shifting to more efficient gasoline/diesel vehicles (e.g., vehicles with better engine efficiency, lighter weight materials, smaller cabin size) as well as shifting to (all and hybrid) EVs, for a given VKT;[102] and
- $\eta^h \eta^u$ is the product of the fuel consumption rate and VKT elasticities, reflecting the partially offsetting increase in fuel use as reductions in the marginal fuel cost of driving lead to a slight increase in use of vehicles.

It is also helpful to define the following:

$$(3) \qquad Rebound\ effect = -\frac{\eta^u \cdot \eta^h}{\eta^u + \eta^h}$$

Where the 'rebound effect' can be interpreted – for example – as the proportionate reduction in the price elasticity due to the feedback effect on vehicle usage from lower marginal fuel costs.

For the industrial sector, η^u reflects changes in consumer demand as higher energy costs are passed forward into higher consumer prices (subject to pass-through assumptions—see below) where the proportionate price increase (and hence η^u) varies by industry subcategory according to the energy intensity of production.

Energy Supply

Fossil fuels

The supply curves for all fossil fuels and countries are taken to be perfectly elastic over the range of climate mitigation policies, implying that unit production costs, within a particular period, for this range are fixed/do not vary with production levels. This is generally a reasonable approximation for oil products for which international markets are well-integrated and most individual countries face a fixed price for importing or exporting the fuel. For coal, supply curves from domestic production are elastic over the longer term (when the quantity of mines can be adjusted), given potentially large reserves available for extraction, while coal importers generally face a fixed regional price, albeit one that varies with local transportation costs. International markets for natural gas are more fragmented than for oil, given the costs of liquifying and re-gasifying the fuel to link markets across certain continents, though again the assumption that unilateral mitigation policies do not affect prices determined on international markets is generally reasonable.

A caveat is that when large energy-consuming countries act simultaneously to cut fuel use, collectively this can exert downward pressure on international fuel prices. This possibility is not explicitly modelled in CPAT, though its effect would be to (slightly) lower the price responsiveness of domestic fuel use, and this responsiveness is readily adjusted in CPAT for such scenarios.

Power sector

Supply curves for electricity production are also perfectly elastic but here the unit production costs vary endogenously with climate mitigation policies. Given its central importance for decarbonization but also the complexity of the power system, two alternative ways of modelling power generation are used in CPAT: an elasticity-based model and a techno-economic hybrid ('engineering') model.

The elasticity-based supply model is a simplified static approach that allows for broad approximations of changes in electricity generation based on changes in relative prices for generation sources (fuels,

[102] The model abstracts from formal substitution between use of gasoline and diesel vehicles, given that carbon pricing tends to increase user prices for gasoline and diesel in roughly the same proportion. Additionally, for many countries, heavy vehicles—which do not really compete with light-duty, gasoline vehicles—account for most diesel consumption.

renewables, and nuclear). The model is easily parameterized to econometric evidence on coal and fuel price elasticities and the implications of alternative assumptions are transparent. The engineering model allows for incorporation of power system complexities at the country level. These include need for system reliability via storage, differences in generation asset turnover rates, and non-linearities in responses of generation due, for example, to early retirement of existing coal assets. Each model serves as a check on the other to allow, for example, for identification of key factors limiting the rate of decarbonization in power systems (need for system stability or limits on the scaleup of renewables, for example). For results, users can choose between models or take an average of the two.

Elasticity-based electricity supply model

In this model, the unit cost of producing electricity at the industry level, denoted *c*, is determined by a share-weighted average of generation costs for different fuels. That is:

$$(4) \qquad c = \Sigma_i \theta^i \cdot g^i$$

where θ^i is the share of fuel *i* in total generation and g^i is the full cost (see below) of producing and delivering a unit of electricity using fuel *i*, with fuels potentially including coal, natural gas, oil, wind, solar, nuclear, hydro, biomass, and other renewables.

Generation shares are determined as follows:

$$(5) \qquad \theta^i = \theta_0^i \cdot \left\{ (\hat{g}^i)^{\varepsilon^i} + \Sigma_{j \neq i} \theta_0^j \left[1 - (\hat{g}^j)^{\varepsilon^j} \right] / (1 - \theta_0^j \right\}$$

where *i*, *j* index fuels, subscript 0 indicates a generation share in the BAU (prior to mitigation policy), and ˆ indicates a proportionate change in unit costs relative to the BAU (e.g., caused by a carbon tax). Expression (5) summarizes the impact on the generation share for fuel *i* in response to policy-induced changes in its own generation cost, and in the generation cost of other fuels. Specifically, $\varepsilon^i < 0$ is the 'conditional' own-price elasticity of generation for fuel *i*, that is, the percent reduction in fuel *i* due to switching from that fuel to other fuels, per a one-percent increase in fuel *i*'s generation cost, conditional on a fixed level of electricity generation.

The switching to fuel *i* from an own cost-induced reduction in the use of fuel *j* is proportional to fuel *i*'s initial share in generation from fuels other than *j.* This is a neutral assumption in the sense that if all generation costs increase by the same proportion, or there is a price or policy-induced change in electricity demand, then generation shares stay constant. Note that proportionate increases in the generation cost for a particular fuel have a progressively smaller impact on reducing that fuel's generation share—implicitly this represents the increasing marginal cost associated with reducing use of that fuel.

The generation costs of each fuel include the variable (fuel, labor) and fixed costs (upfront investment, maintenance, transmission, and distribution) expressed on an annualized basis, where all costs for each fuel type decline at a fixed annual rate reflecting technological improvements (e.g., from replacement of more efficient capital over time).

Techno-economic ('engineering') electricity supply model

There are significant complexities in the power sector – such as needs for baseload capacity, system stability, and limits on rates of growth of renewables – that cannot be captured in an elasticity-based approach. For example, as the cost of renewables continues to decline, new solar and wind generation can become cheaper than existing fossil-fuel generation (coal, oil, and natural gas), hence causing early retirement of existing fuel assets.[103] However, there is also a need for reliability in the dispatch of generation assets whereas renewables are intermittent (sunlight and wind patterns vary throughout the day and year). Hence more renewables impose additional costs on the system which rise with the share of renewables (as more long-term storage is required, such as hydrolysis systems).

[103] Market-induced early retirement is one of the principal factors determining the responsiveness of power system models. For discussion and a model intercomparison see Ruhnau and others (2022).

CPAT's mitigation module, therefore, also includes a second, technology-explicit hybrid economic ('techno-economic' or 'engineering') model of the power sector.[104] This is a streamlined version of the highly detailed, country-specific power sector planning models used elsewhere, such as in the World Bank's Electricity Planning Model (EPM).[105]

Power systems involve two primary optimization 'decisions':

1. *Dispatch decision* – given the stock of existing generation assets and incorporating power system needs (for reliability, storage, and peaking at different times during the day, for example), power systems need to decide which assets will be used for generating electricity. This is largely determined by variable costs of generation assets (which are low for renewables and nuclear and dependent on the variable costs of fuels for coal, natural gas, oil, and biomass, for example) and any contractual obligations of the power system (the presence of purchasing power agreements, PPAs, for example).

2. *Investment decision* – there is a need each year for additional investments in new generation assets, depending on the level of retirement of existing generation sources and power demand. This depends critically on the forward-looking costs of different generation sources (levelized costs of electricity, LCOE), as well any physical limits (such as those inhibiting the scaleup of wind and solar such as permitting and land supply issues) and system stability requirements (for short- and long-term storage, which grows with the share of intermittent renewables).

The technoeconomic model addresses these decisions in turn. For dispatch, power demand is estimated per the above standardized energy demand equation, with power demand separated by sector (industries, transport, and buildings).[106] Given the stock of existing generation assets, inflexible capacity (renewables, specifically, solar, wind and hydro) are dispatched first at fixed, historical capacity factors. Semi-flexible assets (nuclear, biomass, and oil generation) are dispatched next, and can be ramped downwards if power demand falls (unlike renewables). The remaining power demand is allocated to fully flexible capacity (coal and natural gas) depending on their variable costs according to a logit formula (see below) and assuming historical capacity factors.

For investment, existing capacity is then retired according to country-specific schedules for coal and a linear retirement assumption (depending on estimated economic life) for other generation assets. This can yield a shortfall between existing and needed capacity (in case of growing power demand and/or rapid retirement rates, for example), necessitating investment in new capacity.[107] Needed additions are allocated per a logit formula (below) based on forward-looking levelized costs by generation type, subject to supply constraints (on the rate of scaleup of solar and wind[108]) and the needs for system stability (which require short- and, then, long-term storage as the share of variable renewables rises).

The general logit formula for allocating dispatch to flexible capacity and for investment into new generation sources is as follows:

$$(6) \qquad \frac{x_{ocft}}{\sum_f x_{ocft}} = \frac{e^{-K.c}}{\sum_i e^{-K.c}}$$

where $\frac{x_{ocft}}{\sum_f x_{ocft}}$ is the proportion (i.e. investment, $x = inv$, or generation $x = gen$) allocated to generation type f, and c_i is the relative cost of generation type f (i.e. the total LCOE in the case of investment or variable costs i in the case of dispatch, including any taxes net of subsidies).

[104] For detailed discussion of the technoeconomic power model, refer to documentation on the WB's CPAT webpage.

[105] See Chattopadhyay and others (2018).

[106] Transmission losses, net exports and power industry own use are assumed to be a fixed proportion of power demand, based on historical data.

[107] Investments are based on the gap between the current year's demand and the previous year's capacity less the current year's retirements. It is assumed that all generation sources can be scaled up within a year except for nuclear and hydro where it is assumed new generation assets come on-line after 7 years.

[108] Which vary by country where data is available, or otherwise a default setting equal to a percentage of the previous years' total capacity for solar and wind.

To ensure the model is kept up-to-date, historical generation shares are calibrated to match the most recently observed data (e.g., the base year may be 2019 but generation shares up to 2021 are known for some or all countries), and several other adjustments are made.[109] The technoeconomic model is highly adaptable, with users able to finely tune parameters and override the model in different ways (e.g., by forcing a specific investment schedule into new generation assets based on country plans).

Market Equilibrium and Prices for All Energy Sectors

Firms in each energy sector supply whatever is demanded by (household and industrial) consumers for a particular fuel product at supply prices (see below), denoted p^S, that are fixed within a given period. The retail price faced by (household and industrial) fuel consumers, denoted p^R , is given by:

$$p^R = (p^S + \tau^{excise})(1 + \tau^{VAT}) \quad (7)$$

where τ^{excise} is a pre-existing excise (or any other) tax on fuel use which is negative in the case of consumer-side fuel subsidies (e.g., where energy producers hold domestic prices down below international levels) and τ^{VAT} is the rate of the value-added[110] (or general consumption) tax applied to the fuel (if it is consumed at the household level). Pre-existing carbon taxes and/or ETS permit prices are also incorporated into τ^{excise}.

CPAT allows for the optional inclusion of scalars to reflect different assumptions about the pass-through of carbon pricing into higher prices for fuels, electricity, and industrial products. Pass-through may be less than 100 percent in practice reflecting, for example, institutional price setting for fuels and electricity, market power, or limited ability to pass higher costs into product prices due to international competition in industry (see also discussion in Annex II).

Mitigation Policy Options

Several climate mitigation policies can be modelled in CPAT. This includes explicit carbon pricing[111] policies, such as:

1. **Carbon taxes.** This policy could represent a carbon tax applied to the supply of fossil fuels in proportion to their carbon content. It is modelled by adding to the pre-existing tax on a particular fuel a charge equal to the product of the CO_2 emissions factor for that fuel and the tax rate on CO_2. The carbon tax can be comprehensive in applying to all fuels and sectors, or exemptions can be applied for individual fuels and sectors (with the option to phase out exemptions over time). To the extent they are passed forward, carbon taxes are reflected in higher fossil fuel prices. The increase in electricity prices has two components: (i) the pure abatement costs which reflect increase in generation costs per unit due to the shifting to cleaner, but costlier, generation fuels; and (ii) the tax on remaining emissions per unit of production (or carbon charges on fossil fuel inputs per unit of production).[112]

2. **Emissions Trading Schemes (ETSs).** These policies are modelled by their virtual tax, or 'shadow price' equivalent,[113] that is, the ETS is modelled by the equivalent carbon charges on the fuels used in sectors to which the ETS is applied (CPAT is deterministic and does not capture uncertainty over

[109] For example, renewables technologies are more metals- and minerals- intensive than non-renewables (Stuermer, Boer, and Pescatori 2021), hence rising metals/minerals costs can be expected to increase the relative cost of new renewables investment. Considering the surge in international metals and mineral prices in 2021-2022, projected capital expenditure costs for investment in new renewable and non-renewable capacity were, therefore, upscaled by 10 percent and 5 percent in 2022 respectively, declining to a 5 percent and 2.5 percent permanent increase in 2030 compared with previous projections. For the IMF's Energy Transition Metals Index, see: https://www.imf.org/en/Research/commodity-prices

[110] In CPAT, adding existing excise taxes to the VAT base is a user choice. Generally, excises are part of the VAT base.

[111] Explicit carbon prices are schemes where the costs of fuels or emissions depend on actual CO_2 (or CO_2e) emissions.

[112] Proportionate price increases for specific industries vary with the emissions intensity of their production.

[113] A shadow price expresses the effect of a quantity-based policy like an ETS or emission rate standard in terms of a tax that would produce equivalent behavioral responses to the quantity-based policy.

emissions prices associated with ETSs). A scalar adjustment, set at a default value of 0.9[114], is applied to the emissions price, however, which implies a (moderately smaller) behavioral response from the ETS compared with an equivalent carbon tax at the same rate. This scalar could represent: (i) exclusion of small-emitting firms from an ETS applied downstream to large firms in the power and industry sectors; (ii) higher price uncertainty under an ETS compared with a tax which potentially dampens investment incentives for low-carbon technologies; and (iii) grandfathering of allowances to incumbent firms, creating barriers to new entrants and potentially forestalling innovation.[115]

Carbon taxes and ETSs have many desirable attributes compared with other mitigation policies, and hence ideally would form the central policy for mitigation strategies.[116] However, carbon pricing alone may not achieve countries' mitigation goals, especially in sectors where low-carbon technologies and hence abatement costs are high.[117]

Other policies beyond pricing will be needed, many of which can be modelled in CPAT. These include:

3. **Taxes on individual fuels, electricity, and methane emissions.** These policies are modelled as a new, or increase in existing, fuel or electricity taxes. For fuels and electricity, the user can choose to exempt specific fuels or energy-consuming sectors, and for methane the user can choose which major sources the fee applies to.

4. **Renewable energy subsidies.** Subsidies for renewable generation are modelled in CPAT via a subsidy providing a proportionate reduction in the per-unit generation cost for renewables (feed-in subsidy). Subsidies for other clean energy technologies such as electric vehicles (EV) are not currently modelled in CPAT, though future improvements to the transport sector modelling may allow for this.

5. **VAT harmonization*.*** Many countries have preferential rates for fuels or household electricity consumption in different sectors, which deviates from the benchmark of a standardized rate applied to all consumer products. The user can select to harmonize VAT on fuels and electricity and, in the case of corrective taxation, can choose to impose VAT on top of the sum of supply costs plus taxes including taxes for externalities.[118]

6. **Emission rate/energy efficiency regulations.** CPAT can model various regulatory policies through a shadow pricing approach, whereby a policy such as an emissions rate regulation only impacts the efficiency margin rather than the direct demand response (implicitly the regulations allow for credit trading, which leads to a unform emissions price across firms). As a result, CPAT can model implicitly: CO_2 emission rate standards (e.g., per kWh of power generation, per unit of production for individual industries, or per VKT for vehicles) or energy efficiency standards (e.g., for electricity demand, and energy use in the industry, transport, and building sectors). These policies reduce the emissions or energy intensity of a sector but without the same demand response (e.g., reductions in VKT) as under carbon pricing because they do not involve the pass-through of carbon tax revenues (or allowance rents) in higher prices (e.g., for electricity or gasoline). They also produce a moderately offsetting increase in emissions through the 'rebound effect', which is captured in the model.

7. **Feebates.** In their pure form, 'fee and rebate' regimes ('feebates') provide a revenue-neutral, sliding scale of fees on activities (like power generation) or products (like vehicles) with above-average emission rates and a sliding scale of rebates for activities or products with below-average emission rates. Feebates are the fiscal analog of (tradable) emission rates or energy efficiency regulations and

[114] The efficiency gap between the carbon tax and ETS can be adjusted by the user.

[115] All these factors are likely modest relative to economy-wide emissions reductions created by an ETS. For example, small-scale emitters exempted from the EU ETS in 2020 accounted for 6.9 percent of EU-wide CO_2 emissions (see www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1). See also Cramton and Kerr (2002), Prest and others (2021) on the mitigation implications of grandfathering.

[116] For discussion of the merits and relative design attributes of carbon taxes and ETSs refer to Parry and others (2022a).

[117] For a discussion of low-carbon technological innovation and policies needed to accelerate technology transfer refer to Pigato and others (2020b). For data on global low-carbon technology trade see Howell and others (2023).

[118] See Parry and others (2021c).

are also incorporated in CPAT through shadow prices. For example, in terms of equation (1), a fuel tax or carbon price increases p_t in the expressions for both u_t and h_t, while a feebate adds a shadow price to p_t in the expression for h_t only.

8. **Fossil fuel subsidy reform.** CPAT uses the latest available dataset on fossil fuel subsidies by fuel product, sector, and country from IMF (Parry and others 2021c). CPAT can model partial reforms (removing explicit subsidies) or full reforms (to also apply corrective taxes to internalize external costs, i.e. implicit subsidies).[119]

9. **Energy price liberalization.** Some countries control the prices of fuels domestically through explicit or implicit subsidy regimes. CPAT contains estimates of the pass-through rates for individual fuels in sectors for many countries, based on regressions on a long historical dataset of domestic fuel price changes with respect to international prices which are then bucketed (assuming pass-through rates of 0.25, 0.5, 0.75 or 1.0, though for most fuels and countries a 1.0 pass-through rate is assumed). For countries with price controls, these can be phased out gradually in the policy scenario, thereby impacting energy, emissions, and revenues.

10. **Policy mixes.** Various policy combinations are possible in CPAT, including carbon pricing, fuel tax changes, or regulations combined with fossil fuel subsidy reform, energy price liberalization, and/or renewable subsidies. Future iterations of CPAT will allow for a more diverse range of policy mixes, which is increasingly relevant given the diverse strategies adopted by countries.[120]

Other policies that can have an impact on energy consumption and emissions are not currently included in CPAT. These include public investments (e.g., in smart grids, public transportation), low-carbon fuel standards, biofuel mandates, building codes, incentives for specific technologies (e.g., geothermal power, nuclear, carbon capture and storage, CCS), emission rate standards for non-road vehicles, measures for extractive industries (e.g., moratoria on extraction, charges on production or fugitive emissions), and mitigation instruments beyond the energy sector. In many cases however, these policies only have modest impacts on emissions. Broader policies to promote R&D into critical technologies are also beyond the scope of CPAT at present.

Energy Sector: Key Assumptions

Energy demand

Consumption of energy sources by sector and country for the latest available year is compiled from IEA, Enerdata and the UN. Electricity demand is modelled separately for the buildings, industry, and transport sectors, focusing on domestic generation (i.e., including exported generation where fuels are combusted domestically, but not imported generation).

For fuel and electricity consumed by households and industry, energy demand is projected forward using equation (1). For fuels used in power generation, consumption is projected forward with the elasticity- and engineering-based models and then averaged in the default case.

GDP

Real GDP is projected using the IMF’s latest World Economic Outlook (WEO) estimates (e.g., from IMF 2022) which provides five years of projected GDP (including the current year). These projections are extended into the long term using estimates derived from the IMF-ENV CGE model, which assumes gradual convergence between developing and developed countries and accounts for structural change. Deviations in GDP in the policy scenario are estimated using the approach described above.

[119] ‘Explicit’ fossil fuel subsidies reflect undercharging for supply costs only. ‘Implicit’ fossil fuel subsidies reflect undercharging for environmental costs and forgone consumption taxes – see Parry and others (2021c).

[120] For example, for a description of sectoral targets and policies of G20 countries plus their mapping (via CPAT) into emissions reductions and their ‘carbon price equivalents’ (CPE), see Black and others (2022a).

Income elasticities of energy demand
There are 32 'base' income elasticities in CPAT covering eight energy sources (coal; natural gas; gasoline; diesel; other oil products like LPG and kerosene; biomass; small-scale renewables like solar PV; and electricity) as well as four sectors (transport including road, rail, aviation and shipping; residential; heavy industry; and public and private services – see Table A.I.1). These elasticities were obtained from the following three-step procedure.

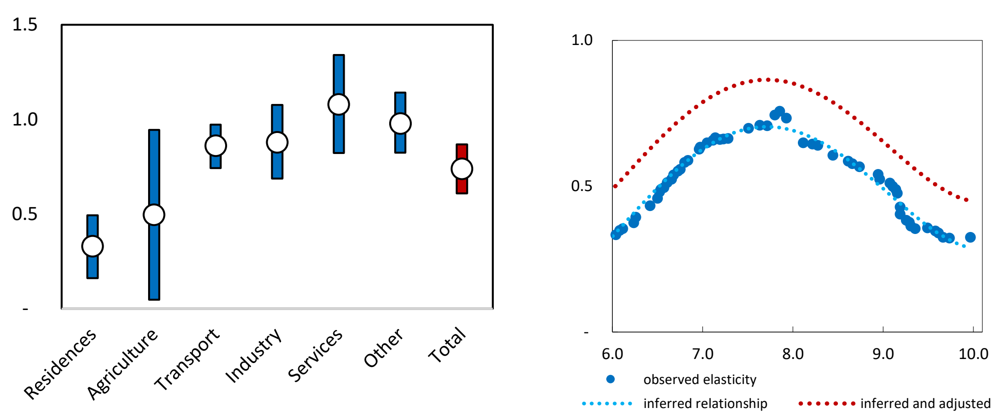
First, base income elasticities for the industry, transport, residential and services sectors are inferred from a large empirical study (Burke and Csereklyei 2016), which covers 132 countries during 1960-2010. Then, fuel-specific elasticities within sectors are derived based on a simple average across a large dataset of income elasticities collected by the authors – this dataset covers over 250 empirical studies and over 4,500 observations of elasticities across countries. These fuel-specific elasticities within sectors are adjusted upwards or downwards such that the weighted global average income elasticity is within one standard deviation of those found for sectors (left panel of Figure A.I.1 below). This mapping exercise ensures that elasticities are fuel- and sector- specific, while being empirically grounded. Broadly, energy demand grows more quickly in services, industry, transport, and the others sector than it does in the residential or services sectors.

Table A.I.1. Base income elasticities of energy demand in CPAT

Income elasticities	Transport	Residential	Industries	Services
Coal	0.00	0.40	0.50	0.70
Natural gas	0.50	0.60	1.00	1.00
Gasoline	0.70	0.50	0.50	0.50
Diesel	0.60	0.50	0.50	0.50
Oil	0.80	0.50	0.90	1.20
Biomass	0.00	0.10	0.10	0.10
Renewables	1.00	0.75	0.75	1.00
Electricity	1.20	0.75	0.75	1.10

Source: IMF Staff using Burke and Csereklyei (2016). Note that the residential and services sectors are separated when estimating energy demand and then re-aggregated into one 'buildings' sector (aligned with UNFCCC inventories).

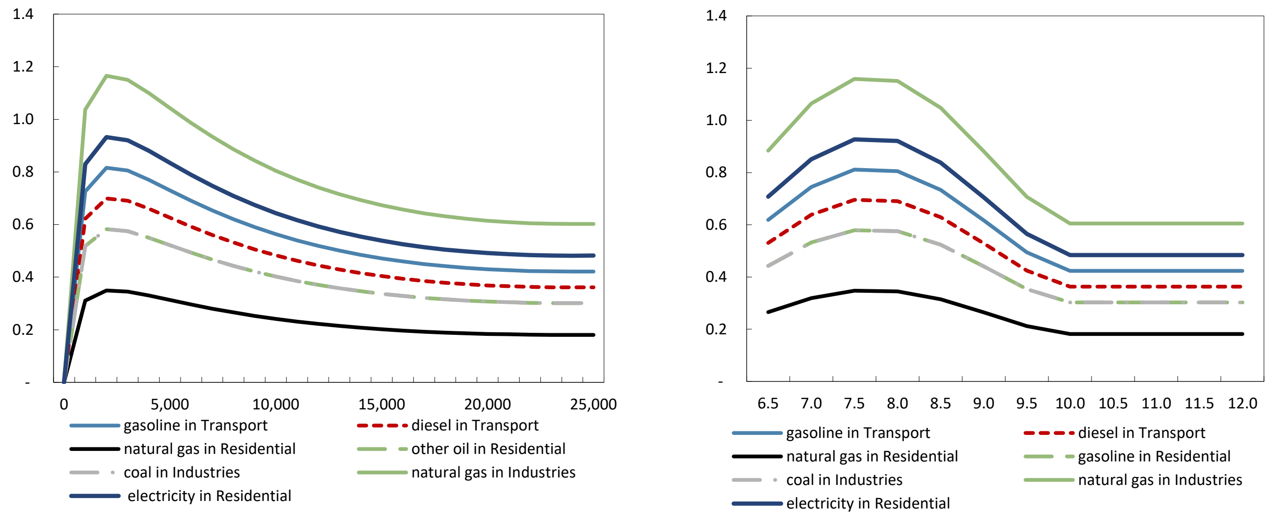
Figure A.I.1. Income elasticities of fuel demand, by sector (left panel, 1960-2010) and by development levels (right panel, unadjusted and adjusted elasticities with respect to log GDP 1985-2010)



Source: left panel from Burke and Csereklyei (2016); right panel inferred from Gertler and others (2016).
Notes: left panel shows includes estimated long-run energy-GDP elasticities (1960-2010), showing mean point estimates and 95-percent confidence intervals. Right panel shows the estimated variation in energy-GDP by mean log GDP levels observed elasticities across countries (1985-2010); this curve is then adjusted upwards such that the average across countries and time matches the global average total income elasticity observed in that same period (0.74 during 1960-2010; from left panel).

Second, income elasticities are adjusted for income per capita of the country considered in each projection period to reflect the broad finding that income elasticities decline with development. This effect could be reflective of the initial rise, and then saturation, of energy-consuming assets as countries develop (e.g., vehicles, refrigerators, air conditioners).[121] Specifically, it is assumed that income elasticities have an inverse-U relation with respect to per-capita income levels. The relationship is derived from Gertler and others (2016) based on a cross-country data analysis for 1985-2010 (right panel of Figure A.I.2), with a modest upward adjustment to ensure the global average income elasticity is consistent with that estimated by Burke and Csereklyei (0.74, 2016) over the longer time horizon 1960-2010.

Figure A.I.2. Example income elasticities adjusted for per capita GDP, selected fuels/sectors by GDP (left) and log GDP (right)



Source: IMF staff based on Burke and Csereklyei (2016) and Gertler and others (2016), .

This adjustment is, then, applied to the base income elasticity for each country over the projection period (varying with each year). The impact for selected fuel-sector pairs is shown in Figure A.I.2. Example income for per capita GDP (left panel) and log GDP (right panel). Income elasticities jump up as countries graduate from being lower-income to a peak around lower-middle income status (at around $3,000 per capita) and then asymptotically decline until reaching the developed country maximum (at around $22,000 per capita).

Lastly, given the lag between emissions data (timely) and energy consumption data (less timely), adjustments to income elasticities of energy demand are made in early projection years. These adjustments are made via scalars which interact with income elasticities to ensure that energy-related emissions in early years of energy demand projection match those in GHG inventories, and they vary by country and year.[122,123]

<u>Own-price elasticities of demand for energy products consumed by households and firms</u>
A similar, three-step approach is used to parameterize final own-price energy demand according to the total elasticity and its decomposition in equation (2) into usage and intensity elasticities.[124] Note that this covers general energy demand, including for electricity, but does not cover elasticities of demand for fuel

[121] Numerous studies have documented this relationship (e.g., Gertler and others 2016; Zhu and others 2018; Liddle and Huntington 2020; Caron and Fally 2022).

[122] For timely national GHG inventories used in CPAT (in addition to more recent quarterly emissions for regions), refer to the IMF's Climate Change Indicators Dashboard – https://climatedata.imf.org/

[123] At the time of writing, there has been a surge in fossil fuel prices globally due, in part, to the Russian invasion of Ukraine. Since this surge took place in the years where price and emissions data are available but consumption data is not, the calibration adjustment in years 2021-2022 on income elasticities is partially reversed in years 2023-2024. In normal times, a gradual reduction in energy prices (as is currently expected by futures markets) would be expected to rapidly increase energy demand, but this may be less likely in coming years, given the unprecedented and highly uncertain nature of the current supply shock to global energy supply.

[124] Empirical studies generally include rebound effects when estimating the total price elasticity of demand.

generation (relevant for the elasticity-based power sector model). The process is as follows: a major meta-study is used to estimate elasticities for fuels, from which sectoral elasticities are then inferred (since CPAT allows for differential elasticities for fuels in different sectors), and finally sense checked to the large in-house elasticity database. These steps are described in turn.

The initial source for price elasticities is a meta-study by Labandeira and others (2017). This includes about 2,000 empirically estimated elasticities from 430 studies with broad global coverage of countries, seven fuels, and four sectors (refer to Table A.I.3 for descriptive statistics). 'Target' estimates of elasticities for fuels and sectors are calculated, assuming that the base is the transport sector, plus deviations for the residential, industrial and services sectors (Table A.I.4).[125] For any statistically insignificant values for fuels within sectoral regressions (e.g., natural gas in the residential sector), it is assumed that the difference between sectoral and base elasticities equals that sectors' general elasticities multiplied by a scalar for all energy sources.[126]

Additionally, there is evidence that price elasticities are slightly higher for developing countries (about 10 percent, except for diesel – see Labandeira and others 2017). Price elasticities are, therefore, adjusted slightly upwards for developing

Table A.I.2. Price elasticities of demand by sector, good, and country from meta study used for parametrization (long-term elasticities)

Sector	# observations	Mean elasticity	Proportion of 'total'
Residential	710	-0.62	1.42
Industrial	266	-0.51	1.17
Commercial	61	-0.72	1.60
Total (assumed transport)	**839**	**-0.44**	
Energy source	**# observations**	**Mean elasticity**	**Adjusted elasticity**
Energy	376	-0.57	0.00
Electricity	538	-0.51	-0.37
Natural gas	230	-0.57	-0.68
Gasoline	469	-0.53	-0.77
Diesel	136	-0.39	-0.44
Heating oil (assumed other oil)	44	-0.54	
Country	**# observations**	**Mean elasticity**	
Developed	1450	-0.52	
Developing	426	-0.55	
Net energy exporter	481	-0.51	
Net energy importer	1395	-0.53	

Source: Labandeira and others (2017).

Table A.I.3. 'Target' price elasticities based on empirical literature

	Base (assumed transport)	Residential	Industrial	Services	*Simple average*
Electricity	-0.37	-0.40	-0.40	-0.66	***-0.46***
Natural gas	-0.68	-0.76	-0.75	-1.01	***-0.80***
Gasoline	-0.77	-0.85	-0.85	-1.15	***-0.91***
Diesel	-0.44	-0.49	-1.18	-0.66	***-0.69***
Heating oil	-0.54	-0.59	-0.59	-0.79	***-0.63***
Simple average	***-0.56***	***-0.62***	***-0.76***	***-0.85***	***-0.70***

Source: IMF staff based on Labandeira and others (2017).

Table A.I.4. Total price elasticities used in CPAT (weighted by developed and developing country emissions)

	Base (assumed transport)	Residential	Industrial	Services	*Simple average*
Electricity	-0.34	-0.42	-0.42	-0.68	***-0.46***
Natural gas	-0.68	-0.69	-0.74	-1.00	***-0.78***
Gasoline	-0.62	-0.79	-0.81	-1.04	***-0.82***
Diesel	-0.44	-0.44	-1.08	-0.68	***-0.66***
Heating oil	-0.56	-0.56	-0.62	-0.79	***-0.63***
Simple average	***-0.53***	***-0.58***	***-0.73***	***-0.84***	***-0.67***

Source: IMF staff.

[125] Transport sector studies account for the highest share of elasticity studies, mostly for gasoline and diesel. For estimates see Tables A.I.1-A.I.4 in Labandeira and others (2017).

[126] For example, the price elasticity for natural gas in the residential sector equals the base elasticity for natural gas (-0.37) times 1.1, as residential energy demand is 10 percent higher for all energy (coefficient on residential is -0.063 compared to a beta coefficient of -0.596, averaging between generalized least squares and fixed effects panel approaches; Tables A.I.1 and A.I.2).

countries (on the extensive margin) such that they are a similar magnitude higher than for developed countries.

Price elasticities used in CPAT are then calibrated to those targets (Table A.I.5). As shown in Table A.I.4, when weighing for developed and developing countries' emissions, elasticities in CPAT are very similar (within 10 percent) to these target elasticities.

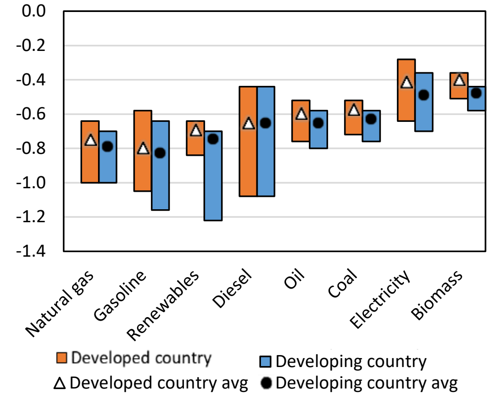
Table A.I.5. Price elasticities of energy demand in CPAT

Price elasticities of demand	**Transport**	**Residential**	**Industries**	**Services**
Own-price elasticities of demand - usage (intensive and extensive margins)				
- coal	-0.27	-0.27	-0.27	-0.37
- natural gas	-0.47	-0.37	-0.47	-0.57
- gasoline	-0.37	-0.47	-0.37	-0.57
- diesel	-0.20	-0.20	-0.60	-0.47
- other oil products	-0.27	-0.27	-0.37	-0.47
- biomass	-0.27	-0.27	-0.27	-0.37
- renewables	-0.47	-0.47	-0.47	-0.67
- electricity	-0.17	-0.27	-0.27	-0.47
Own-price elasticities of demand - efficiency (average fuel economy of energy-using capital)				
- coal	-0.40	-0.40	-0.40	-0.60
- natural gas	-0.40	-0.50	-0.50	-1.00
- gasoline	-0.40	-0.60	-0.70	-1.10
- diesel	-0.30	-0.30	-1.20	-0.40
- oil	-0.40	-0.40	-0.40	-0.60
- biomass	-0.20	-0.20	-0.20	-0.30
- renewables	-0.40	-0.40	-0.40	-0.60
- electricity	-0.20	-0.20	-0.20	-0.40
Memo: implied total demand elasticities				
- coal	*-0.56*	*-0.56*	*-0.56*	*-0.75*
- natural gas	*-0.68*	*-0.69*	*-0.74*	*-1.00*
- gasoline	*-0.62*	*-0.79*	*-0.81*	*-1.04*
- diesel	*-0.44*	*-0.44*	*-1.08*	*-0.68*
- oil	*-0.56*	*-0.56*	*-0.62*	*-0.79*
- biomass	*-0.42*	*-0.42*	*-0.42*	*-0.56*
- renewables	*-0.68*	*-0.68*	*-0.68*	*-0.87*
- electricity	*-0.34*	*-0.42*	*-0.42*	*-0.68*
simple average	***-0.54***	***-0.57***	***-0.67***	***-0.80***

Source: IMF staff. Figures show weighted average price elasticities used for developed and developing countries. For developing countries, efficiency elasticities are uniformly increased (in absolute terms) by 0.1 (except for diesel elasticities).

Figure A.I.3 shows the distribution of price elasticities for different energy sources between income groups and across sectors (transport, residential, industries, services). The largest elasticity within sectors is for diesel, where the transport sector is relatively inelastic (price elasticity of -0.44 in both developed and developing countries) compared with the industrial sector (-1.08). Per the above, elasticities are slightly higher in developing countries for all energy sources except for diesel. Across sectors, elasticates range from about -0.2 to about -1.2.

Figure A.I.3. Price elasticities used in CPAT by sector, energy and income level



Source: IMF staff. Note: shows range and unweighted mean of price elasticities of demand used by fuel across sectors for developed and developing countries.

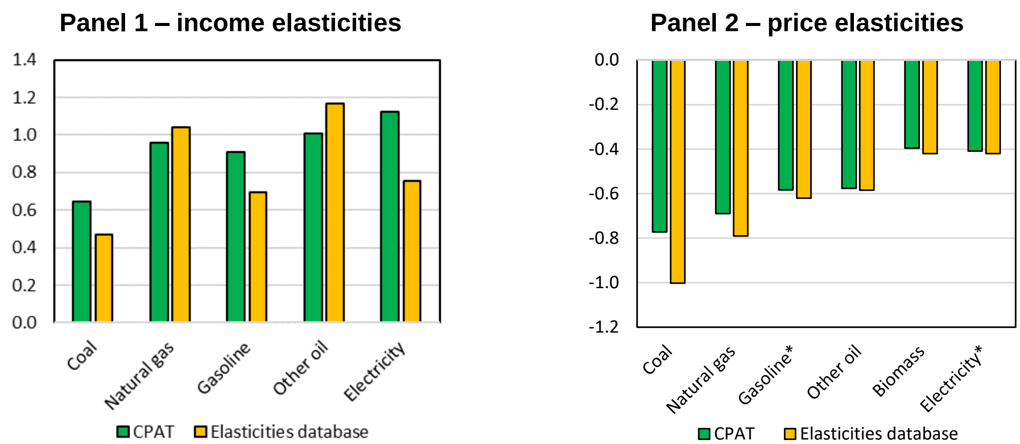
<u>Cross-price elasticities</u>

CPAT contains three substitution or cross-price elasticities to account for the risk that households that face increases in costs for residential heating and cooking fuels shift to informal fuels like biomass. This 'leakage' effect can have a negative impact on household air pollution and, hence, welfare, which is calculated by CPAT's air pollution module. These cross-price elasticities (biomass with respect to LPG, biomass with respect to kerosene, and gasoline with respect to diesel) are parameterized to the same broad literature review process described above and are 0.25 in each case.

<u>Sense-checking elasticities</u>

Income and price elasticities are sense-checked in several ways. First, as mentioned above, they are checked against the large, independently collected database of elasticities estimated by the empirical literature which includes over 250 studies and 4,500 elasticity observations. In Figure A1.4, CPAT's income elasticities are examined at the global average GDP per capita in the median year of the period covered within the studies of the elasticities database (1985). Price elasticities are weighted by developed and developing country average shares of emissions in 2019 (see figures above). Both are then weighted by the fuel's share in total global emissions. To aid comparison, the empirically observed elasticities in the database are weighted by the inverse of their t-statistics (to give more weight to more statistically significant results) and then by the fuel's share in total global emissions.

Figure A.I.4. Energy-weighted price and income elasticities used in CPAT compared to a large database of empirical observations



Source: IMF staff. Note: * indicates that simple average was used instead due to a lack of studies reporting t-statistics.

There is some variation between weighted price and income elasticities in CPAT versus the database, but the differences are generally not significant. For income elasticities, the largest difference is for electricity, and gasoline: where CPAT uses 1.1 and 0.9, the database shows 0.8 and 0.7, respectively. However, it is expected that electrification of the transport sector will result in greater growth in demand for electricity and lower growth for gasoline demand than is historically observed for a given income level.

Second, income and price elasticities are sense-checked through model intercomparisons of BAU energy consumption and emissions projections, versus other global, regional, and country-specific models. The baseline emissions projections and price responsiveness of emissions are broadly in line with those of other models.

Third, elasticities are sense checked for their ramifications for rebound effects. Rebound effects are the partially offsetting increases in energy demand due to induced energy efficiency improvements which lowers marginal costs of energy consumption and hence slightly raises demand. For example, a more efficient vehicle fleet will raise the demand for vehicle usage. The rebound effect can be defined as follows:

$$(8) \qquad Rebound\ effect = -\frac{\eta^u \cdot \eta^h}{\eta^u + \eta^h}$$

When extrapolating rebound effects based on Table AI.2, they are broadly in line with the empirical literature. For example, the simple average rebound effect across fuels and sectors ranges from 13 to 26 percent, which broadly in line with empirical studies.[127]

It should be noted that elasticities used in CPAT are ‘long-term’ elasticities. CPAT abstracts from short-term vs. long-term effects, though the empirical literature generally does not specify the long term in years, and the impacts (on e.g., energy consumption and emissions) beyond a few years following policy changes do not change much. Lastly, as noted in the main text, price elasticities listed above may be understated, as evidence suggests policy-induced price changes may elicit a stronger response than market-induced changes in prices, and there may be non-linearities in responsiveness to strong policy changes (due, e.g., to carbon capture technologies becoming economical at very high prices). These elasticities are, therefore, conservative.

Autonomous rate of technological change

This rate is set at between 0.5 and 1 percent per year for each fuel-sector pair (Table A.I.6) based on typical modelling assumptions.[128] Rates vary across sectors and fuels to reflect assumed differences in rates of technological change. For example, the fuel economy of vehicles has been steadily improving globally, leading to an annual decrease in energy consumed per kilometer travelled of 1.7 percent for cars and light trucks from 2000 to 2020. By contrast, the efficiency improvements of residential buildings rose by an annual average of 1.3 percent between 2000 and 2020 (IEA 2022b). Note, however, that in both cases these efficiency improvements have been partially offset by compositional changes, as the average vehicle size and floor space of residences have both grown.

Table A.I.6. Exogenous efficiency improvements in energy-consuming capital goods

Autonomous efficiency improvment:	Transport	Residential	Industries	Services
Coal	1.0%	0.5%	0.5%	0.5%
Natural gas	1.0%	1.0%	1.0%	1.0%
Oil Products	1.0%	0.5%	0.5%	0.5%
Biomass	1.0%	0.5%	0.5%	0.5%
Renewables	1.0%	0.5%	0.5%	0.5%
Electricity	1.0%	0.5%	0.5%	0.5%

Source: IMF staff.

Power sector: elasticity-based power supply model

127 In a meta-analysis of 74 studies, Dimitropoulos and others (2018) find rebound effects of about 26 percent.

128 For example, Webster and others (2008) Table 1. Baseline emissions projections are only moderately sensitive to alternative assumptions.

Generation shares. Power generation shares by fuel type are taken for over 200 countries from IEA, Enerdata, UN and other sources.

Own-price elasticities for generation fuels (conditional on total electricity output). Empirical studies tend to suggest that coal is only moderately price responsive. For example, a survey of eight studies for various advanced countries, China, and India puts the short-run coal price elasticity at -0.15 to -0.6.[129] For the United States, simulations from a variant of the US Department of Energy's National Energy Modeling System (NEMS) model suggests a coal price elasticity of around -0.15 (with fuel switching rather than reduced electricity demand accounting for over 80 percent of the response).[130] Other studies suggest a somewhat larger responsiveness. For example, EIA (2014) estimates that a $34 per ton carbon tax (raising coal prices by about 150 percent) reduces US coal use by 32 percent in 2040, while an $85 per ton carbon tax reduces coal use by 90 percent.[131] Finally, a study for China reports coal price elasticities of -0.3 to -0.7.[132]

CPAT assumes that the rapid (and continued future) decline in the costs of renewable energy will likely increase the price responsiveness of coal use relative to previous estimates, and could induce significant technological innovation.[133] With this in mind, a coal generation price elasticity of -0.7 is assumed here for all countries.[134] For other generation fuels, the elasticity is assumed to be -0.5.

Annual rate of autonomous productivity improvement. Productivity improvements at power plants reflect improvements in technical efficiency and gradual retirement of older, less efficient plants. For coal, annual average productivity growth is taken to be 0.5 percent as the coal plants have reached close to their maximum efficiency levels (higher thermal efficiency requires increasing boiler temperatures and new plants tend to be close to the physical limit of super and ultra-supercritical temperatures). For natural gas, nuclear, and hydro, it is assumed that there is more room for productivity improvements and an annual growth rate of 1 percent is assumed. For renewables, which have declined rapidly in costs historically, a productivity growth rate of 5 percent is used (i.e., costs halve every 15 years).[135]

Non-fuel generation costs. Generation costs beyond the price of fuel are based on a large dataset of generation costs across countries. This includes operations and management costs, capital costs, and system integration costs.[136]

Energy prices

Historical energy prices are collected from many sources, including IMF and World Bank country economists, complemented by data from IEA, Eurostat, Enerdata, Global Petrol Prices, and others[137]. This accounts for potential variation in prices and supply costs across different sectors, and is described with

[129] Trüby and Paulus (2012), Table 5.

[130] See Krupnick and others (2010). This simulation was for a carbon price which also raises natural gas prices, thereby dampening some of the reduction in coal use.

[131] Much of the difference between EIA (2014) and Krupnick and others (2010) is due to different assumptions about the expansion of nuclear power and renewables in response to higher coal prices—Krupnick and others (2010) adjusted the NEMS model to limit this expansion to reflect practical constraints (e.g., public opposition to site development).

[132] Burke and Liao (2015).

[133] For example, Fried (2018) estimates that induced innovation increases the price-responsiveness of US CO_2 emissions by about a fifth. See Perino and Requate (2012) for further discussion.

[134] The degree of substitution among fossil and non-fossil fuel generation sources is, however, limited in practice, for example, due to the intermittency of renewables, their location away from population centers, and public opposition to nuclear power.

[135] See Way and others (2021).

[136] System integration costs are higher for variable renewable energy sources (wind, solar, and other renewables), which require an increasing level of storage at higher rates of generation shares in the power system.

[137] Except for the cases when the data for countries is provided by IMF or WB country desks, the retail prices are an average of at least two independent sources.

accompanying spreadsheets made available in Parry and others (2021c).[138] Prices are collected for many years and countries for liquid fuels (gasoline, diesel, kerosene, LPG), for coal and natural gas (industrial, residential, and power), and electricity (for industrial and residential sectors).

Retail prices. These prices are collected for many countries, sectors, and fuels—where they are missing they are assumed equal to supply costs, with VAT included for residential use if VAT is charged on a given fuel.

Supply prices. These prices for fossil fuels are calculated using the following equations:

$$p^S = \theta p^{int} + (1-\theta) p^{dom}, \quad p^{int} = p^{imp} + m^{int}, \; p^{dom} = c^{ext} + m^{ext} \tag{9}$$

where:

$0 \leq \theta \leq 1$ is the share of fuel supply coming from imports and $(1-\theta)$ is the share from domestic production);

p^{int} is the price received by domestic firms that import fuel products and sell them domestically

p^{dom} is the production cost plus any taxes imposed on extractive companies and any costs incurred between the point of extraction and delivery to the end-user (e.g., transportation)

p^{imp} is the international reference price of the fuel

m^{int} are margins for imported fuel related to non-tax costs incurred between the point of importation and delivery to the end-user (e.g., transportation)

c^{ext} is the domestic extraction cost plus taxes imported on extractive companies, per unit

m^{ext} are margins for domestically produced fuel related to non-tax costs incurred between the point of extraction and delivery to the end-user (e.g., transportation)

The supply price is a domestic consumption-weighted average of the prices for imported and domestic production.[139] The price for fuel imports is the international reference price for the fuel product plus margins (e.g., domestic processing/transport/distribution costs if crude oil is imported, or domestic transport/distribution costs if gasoline is imported). The price for domestic production is the sum of extraction costs, domestic margins, and any production tax (e.g., from royalties, using the IMF's FARI model (Luca and Mesa Puyo 2016).

The components of supply prices (margins, production costs, taxes on production, and import prices) are projected forward, assuming that margins and production costs are fixed in real terms while taxes on production and import prices change based on international reference prices. For projections, CPAT averages over international price projections from IMF World Economic Outlook and the World Bank (2022a), although other options are available within the model. BAU emissions projections and the percent emissions reductions from carbon pricing are both increased with lower fuel price projections (the latter because carbon pricing has a greater proportionate impact on fuel prices).

Fuel taxes. Fuel taxes by country are based on the price-gap approach, that is, the difference between retail and supply prices. They, hence, implicitly reflect the combined effect of excises, any favorable VAT provisions for household fuels, regulated or monopoly price distortions, and carbon pricing. Fuel charges from pre-existing carbon taxes and ETSs are estimated using sources including the World Bank (2022a) and others, converted from \$/tCO2 to \$/energy unit using CO_2 emissions factors. These are kept flat in the baseline, but this assumption can be tweaked by the user. The new carbon tax or ETS is also converted from \$/tCO2 to \$/energy unit using emissions factors. Excise taxes can be added on top or separately, based on user input for each fuel-sector pair.

<u>Fossil fuel subsidies</u>

CPAT prices also include explicit fossil fuel subsidies, both producer subsidies (embedded within supply costs; s_i^{Prod}) and consumer subsidies (within the 'excise and other taxes' component of retail prices)

[138] See www.imf.org/en/Topics/Environment/energy-subsidies.

[139] The portion of a fuel that is domestically produced vs. imported is estimated using energy balances from the IEA and Enerdata, with adjustments to account for re-exports.

s_i^{Cons}.[140] Producer-side subsidies are estimated using external data (Parry and others 2021c, Annex B) on the total value of subsidies, which are then apportioned to their impact on global versus domestic supply costs (varying by fuel given differences in fungibility and segmentation in fuel markets). The domestic component is subtracted from gross supply costs (and can be phased out in the baseline and policy scenario).

$$(10) \quad s_i^{Cons} = s_i^{Fix} + s_i^{Var} \cdot \Delta p_i^{Int};$$

Consumer-side subsidies are the sum of a fixed part (s_i^{Fix}) and a variable part (which varies depending on changes in international prices; $s_i^{Var} \cdot \Delta p_i^{Int}$). The variable part is estimated using panel regressions of the relationship between consumer subsidies and international energy prices to estimate pass-through coefficients.[141] Countries' fuel-sector pairs are put into buckets (0 percent, 25 percent, 50 percent, 75 percent and 100 percent, rounded upwards). These are the assumed portion of changes in international prices that are passed-through to domestic prices, with the difference assumed to be changes in consumer subsidies. This reflects price control regimes that countries may have adopted to reduce the volatility of domestic fuel costs relative to international energy prices. The fixed part of consumer subsidies is estimated using the same econometric approach and is the portion of subsidies which does not change with international prices (and hence is kept fixed unless phased out). The total consumer-side subsidy is capped at the average level of previous years' per-unit consumer-side subsidies.

Value-added taxes (VAT)

This is estimated as the VAT rate (for the applicable fuel and sector) times the VAT base—VAT rates come from the IMF's Fiscal Affairs Department Tax Policy Rates Database and the IEA Energy Prices and Taxes Dataset (2022a). VAT rates for non-residential energy consumption are assumed to be zero since firms can reclaim any VAT paid, resulting in an effective rate of zero.[142]

The VAT rate is the general VAT rate (VAT_{gen}) in the country if the user chooses the 'VAT reform' option or, otherwise, is the VAT revenues (VAT_0) divided by the VAT base (VB_0) in the base (2021) year. If the user chooses optimal taxation, the VAT base will include externalities and will be calculated as a sum of supply costs (sp_t) and excises and other taxes (exo_t). Otherwise, the VAT base is assumed to equal supply costs. Depending on the user inputs, the VAT payment is calculated using one of the four formulas below:

(11) $VAT_t =$

	No VAT reform	VAT reform
Externalities are part of the VAT base (optimal taxation)	$\frac{VAT_0}{VB_0} \cdot (sp_t + exo_t)$	$VAT_{gen} \cdot (sp_t + exo_t)$
Externalities are not included in the VAT base	$\frac{VAT_0}{VB_0} \cdot (sp_t)$	$VAT_{gen} \cdot (sp_t)$

Other fixed/ad valorem taxes are also estimated for each fuel and sector. If a country has a fixed tax regime, this component is equal to the base year's (2021) value. If a country has an ad-valorem tax regime, CPAT pplies the ratio of ad-valorem payment part to supply cost in the base (2021) year to the supply cost in the current year. In the base (2021) year, this component is calculated as a difference between retail price and a sum of supply cost, VAT payment, existing carbon tax, and existing ETS.

International and domestic energy price projections

International fuel price projections are based on an average of those of the IMF and WB for global coal, natural gas, and oil. Coal and natural gas markets are partly segmented (e.g., global LNG or piped natural

[140] Refer to Parry and others (2021c) for estimates of explicit as well as implicit (externalities and forgone VAT) for 192 countries with accompanying spreadsheets.

[141] Countries' fuel-sector pairs are bucketed into 0 percent, 25 percent, 50 percent, 75 percent and 100 percent prices (rounded upwards to account for statistical uncertainty), which reflects the assumed portion of changes in international prices that are passed-through to domestic ones.

[142] This assumption ignores the impact of any VAT exemptions, which result in a firm not being able to recover its VAT paid on inputs.

gas) whereas the global oil market is assumed to be integrated, and projections tend to forecast ahead by five years based on futures markets. Long-term price forecasts beyond this can be varied based on assumptions (e.g. about global decarbonization rates).

Domestic fuel prices are projected based on the following formulas:

$$(12)\quad rp_t = sp_t + VAT_t + exo_t; \quad sp_t = sp_0^{Fix} + (sp_{t-1} - sp_0^{Fix}) \cdot \Delta p_t^{Int} + \theta \cdot ps_t;$$

where:

- rp_t is the retail price for each energy source in time t
- sp_t is the supply cost for each energy source in time t, and is calculated each year linked to:
- sp_0^{Fix} a fixed part based on transportation and distribution margins and a floating part which varies with:
  - Δp_t^{Int} the change in the globally traded price for the energy good
  - θ the phase-out factor share (0 to 1) of producer-side subsidies the user chooses to phase out
  - ps_t the producer-side fuel subsidy's impact on consumer prices (from the IMF's latest Fossil Fuel Subsidy dataset[143]), fixed in real terms
- VAT_t is VAT or sales tax charged per unit of energy (ad valorem or fixed in per-unit terms), defined in equation (11) above
- exo_t is total excise and other taxes. This is defined according to:

$$(13)\quad exo_t = ecp_t + ncp_t + fap_t + s_i^{Cons}; \quad ecp_t = ecpr_t \cdot ec_t^s \cdot ec_t^f \cdot ef_0; \quad ncp_t = ncpr_t \cdot nc_t^s \cdot nc_t^f \cdot ef_0;$$

$$(14)\quad fap_t = \begin{cases} rp_0 - sp_0 - vat_0 - ecp_0 - s_0^{Cons} & if\ fixed\ tax\ regime \\ \frac{rp_0 - sp_0 - vat_0 - ecp_0 - s_0^{Cons}}{sp_0} \cdot sp_{t-1} & if\ ad-valorem\ tax\ regime \end{cases}$$

where:

- $ecpr_t$ is the existing carbon price (carbon tax and/or ETS permit price), calculated based on historical rates ($ecpr_t$), emissions factors (ef_0), and sectoral (ec_t^s) and fuel (ec_t^f) coverage (from the World Bank's Carbon Pricing Dashboard)[144],
- ncp_t is the new policy component (e.g. new carbon pricing or new excise) – calculated based on the rate of the carbon pricing policy ($ncpr_t$), emissions factors (ef_0), and chosen sectoral (nc_t^s) and fuel (nc_t^f) coverage,
- fap_t is a fixed/ad-valorem part. This is a balancing item which is equal to the part of the price gap (difference between retail (rp_0) and supply prices (sp_0)) that is not covered by taxes/subsidies listed above: VAT (vat_0), existing carbon pricing (ecp_0), and consumer-side subsidies (s_0^{Cons}). It is fixed in in base year terms (average 2018-2021) for countries with fixed excise taxes, or a proportion to the previous year's supply cost if the country has an ad-valorem excise tax regime
- s_i^{Cons} is the consumer-side subsidy, defined in equation (10) above

For electricity, the supply cost is the domestic production cost or cost-recovery price, with costs evaluated at domestic fuel prices. Electricity prices are projected forward using changes in fuel prices and generation shares, averaged over the two power supply models (see above).

Impacts of Policies and Targets

<u>CO_2 and other GHG emissions</u>

CO_2 emissions from fossil fuel combustion are given by the consumption of each fossil fuel product, aggregated across sectors, multiplied by the CO_2 emissions factor for that fuel product, and then

[143] Public versions of the dataset, which are updated periodically, can be found on the IMF's Climate Change Indicators Dashboard: https://climatedata.imf.org/datasets/d48cfd2124954fb0900cef95f2db2724/explore

[144] See https://carbonpricingdashboard.worldbank.org/

aggregated across different fossil fuel products.[145] Industrial process CO_2 emissions such as those from cement scale with energy-CO_2 in the industrial sector. Agricultural CO_2 emissions scale with population and per capita incomes while waste and other emissions scale with population. Methane emissions from agriculture (mostly ruminants, such as cattle and sheep, plus rice farming), waste, and extractives (predominately fugitive emissions and venting from coal and natural gas operations) are estimated using country-specific emissions factors by product, assuming autonomous technical change, GDP growth, and marginal abatement cost curves. In the default policy scenario, non-CO_2 GHGs, except for methane, are assumed to change at the same rate as energy emissions

Revenue

Revenues from climate mitigation policies are calculated net of indirect changes in revenues (or outlays) from pre-existing energy taxes (or subsidies). Direct revenues from carbon pricing are the carbon price times the CO_2 emissions to which they are applied and, in the case of ETSs, the fraction of allowances that are auctioned (rather than freely allocated). Revenues from pre-existing energy taxes are the product of the fuel tax rate (which is negative in the case of fuel subsidies) and the fuel consumption to which they are applied, aggregated across fuels and sectors, plus the product of any electricity tax and the electricity consumption to which it applies. Indirect revenue losses from base erosion are implicitly included, and can be estimated as the difference between revenues from pre-existing energy taxes in the BAU compared with BAU tax rates applied to energy consumption in the policy scenario. Similarly, revenues from new, or increases in existing, energy taxes are the tax increase times the fuel or electricity to which the increase applies, net of indirect revenue changes from pre-existing energy taxes.[146]

For regulations and revenue-neutral feebates there is no direct revenue impact, though there is an indirect revenue loss to the extent these policies erode bases for pre-existing energy taxes. For renewable and clean technology subsidies there is a direct revenue loss equal to the product of the subsidy rate and the base to which it applies plus indirect revenue losses from pre-existing energy taxes.

Domestic environmental co-benefits

Annex III discusses the estimation of the monetized domestic environmental costs from fuel use. The domestic environmental co-benefits of mitigation policies are calculated by the induced reductions in use of a fuel product in a particular sector, multiplied by the corresponding domestic environmental cost per unit, and aggregated across sectors and fuels.

Welfare or efficiency costs and net economic benefits

In CPAT, the welfare costs[147] of policies reflect losses in producer and consumer surplus in fossil fuel markets. These can be roughly interpreted as the annualized costs of using cleaner, but costlier technologies, and of reducing energy consumption below levels households would otherwise prefer. Efficiency costs are calculated using applications and extensions of long-established formulas in the public finance literature (e.g., Harberger 1964) based on second-order approximations.[148] They include three components that are in CPAT and a further component which is not yet in CPAT:

- *Pure abatement costs*. These reflect (1) (most importantly) the annualized costs of adopting cleaner but more expensive technologies, net of any savings in lifetime energy costs and avoided investment in emissions-intensive technologies; and (2) the costs to households and firms from reduced energy use. Pure abatement costs reflect integrals under marginal abatement cost schedules (Figure A.I.5) and, at least for more moderate levels of emissions reductions, are measured with reasonable confidence.

[145] CPAT does not currently include the possibility of carbon capture and storage (CSS), which would reduce emissions factors for fossil fuels used at plants where these technologies are applied. It also does not include consideration of emissions from non-energy use of fuels where there is no combustion but may entail some emissions later in the lifecycle (for example in tarmac, lubricants, or petrochemicals).

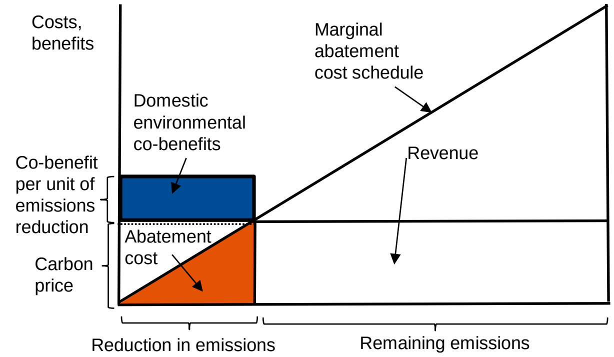
[146] Currently, CPAT does not include pre-existing renewable energy subsidies.

[147] Sometimes also called deadweight losses or excess burdens.

[148] That is, taking fuel and electricity demand curves to be linear over the range of policy-induced fuel changes.

- *Additional welfare effects from pre-existing fuel price distortions*: to the extent carbon mitigation policies reduce use of a fuel subject to a pre-excise tax there is an additional welfare cost equal to the tax wedge times the reduction in fuel use (or a corresponding welfare gain, if there is a pre-existing fuel subsidy). These effects are computed using outputs from CPAT.

Figure A.I.5. Some Components of Welfare Costs and Benefits



Source: IMF staff.

- *Domestic environmental co-benefits***.** These reflect externality benefits from reductions in local air pollution, traffic congestion, and accidents as discussed in the text, while total co-benefits are the emission reduction times the co-benefit per ton of CO_2 reduced Figure 2.1.[149] Climate benefits from cutting emissions are not included in co-benefits as they vary substantially across countries. However, studies suggest these benefits would swamp the pure abatement costs at the global level.[150]

- *Potential fiscal benefits***.** These benefits, which are not in the current version of CPAT, reflect economic efficiency gains from productive use of carbon pricing revenues—that is, revenue raised times the efficiency benefit per dollar recycled (the component is smaller if some revenue is, instead, used for transfers to compensate low-income households). At the same time, there is an offsetting effect as higher production costs and consumer prices lower the real returns to work effort and investment, which can deter labor supply and capital accumulation. The latter effect can dominate the former at higher levels of emissions abatement when the tax base for carbon pricing is narrower.[151]

GDP impacts

The impacts of mitigation policies on GDP (and the general equilibrium effects of changes in GDP affecting energy demand) in CPAT are modelled using fiscal multipliers. Estimates of fiscal multipliers, defined here as the percent change in GDP in subsequent years of the policy from a percent change in tax increases/cuts and/or spending increases/cuts from a one percent of GDP change in energy taxes. These fiscal multipliers are extracted for over 100 countries from the WB's main macrostructural model (MFMOD[152]) in addition to empirically estimated multipliers using a long dataset on the relationship between changes in taxes and GDP over time[153]. These vary by country, year, and tax or expenditure category.

Multipliers are estimated based on a one percentage point of GDP change in taxes (on energy, goods and services, personal income tax or corporate income tax) or expenditures (public investment, transfers, expenditures on goods and services or public wages), and are aggregated at the country income-group level. Impacts on GDP are lagged by one year, i.e., the impact of a policy reform in year 0 affects GDP from year 1 onwards. This approach provides a sense of the likely transition of GDP over time from climate mitigation policy reforms, which can increase growth in some reform cases and decrease growth in others. In the future, it is envisaged that GDP impact estimates will be enhanced, for example, through incorporation of fiscal multipliers from more models and empirical studies, with an emphasis on the disaggregation of channels through which climate mitigation policies affect GDP.

[149] See Parry and others (2022a) on methodologies. Co-benefits also include reductions in traffic congestion and accident externalities from higher road fuel prices.

[150] Rennert and others (2022) put the discounted flow of global climate benefits at $185 per ton of CO_2 reduced. Under a global carbon price of $75 per ton, this would imply climate benefits five times pure abatement costs (per IMF staff calculations).

[151] For example, Parry and others (2012).

[152] For details on MFMOD, refer to Burns and others (2019).

[153] See Schoder (2022).

Nationally Determined Contributions (NDCs)
Signatories of the Paris Agreement submit NDC reports to the UNFCCC, which include stated national or regional emission targets (usually for 2030). However, targets are not reported with a uniform or consistent structure or methodology. Some countries state targets as a percentage reduction from a historical year, others present their targets as an absolute level of emissions while others report their targets as a percentage reduction relative to an assumed "business as usual" (BAU) level of emissions. Coverage of sectors (notably the inclusion of land use, land-use change and forestry, LULUCF) and GHGs varies. Comparisons of mitigation ambition and effort in NDCs are, therefore, difficult.

To overcome this and allow for consistent estimation and comparison of emissions targets, CPAT includes a comprehensive methodology for converting and presenting targets in NDCs. Several countries have not stated absolute emissions levels targets for 2030 (though an increasing number are provided through the UNFCCC). For these countries, economy-wide 2030 emissions targets are converted into an implied target level of emissions in 2030. For countries with a historical baseline (e.g., 2007 or 1990) the target level is estimated using consistent historical data. For countries targeting a percentage reduction versus BAU in a future year (usually 2030), it is assumed that this target is equivalent to the one in CPAT's BAU. Various adjustments are made to account for coverage of GHGs and LULUCF as well as for differences in time periods.

Targets are presented as a target level for total GHG emissions (usually excluding LULUCF[154]) in 2030. For comparison across countries, these absolute emissions targets can be presented as a percentage reduction compared with the mitigation module's BAU. This allows for a comparison of ambition levels across all countries, even for developing countries that are expected to increase absolute emissions to 2030 (but at a slower rate in NDCs).

Multiple targets are shown to aid analysis. Conditional and unconditional (on external financing) NDCs are treated separately, as are targets with and without land use, land-use change and forestry (LULUCF). For countries where the NDC target is a range, an average (corresponding to the midpoint of the range) is assumed. For countries where the estimated NDC target level is above CPAT's estimated BAU, CPAT assumes that these targets are non-binding (CPAT does not assume that the country raises emissions above BAU). For EU countries, national targets include sectors covered by the EU Emissions Trading System (EU ETS) and Effort Sharing Regulation (ESR). Reductions in both ETS and ESR sectors are assumed to increase in stringency to achieve the EU's revised target (55 percent reduction in GHGs compared with 1990 levels) at a similar level as the one required to achieve the EU's previous target (40 percent reduction compared with 1990 levels). Implied NDC estimates are periodically updated as countries revise or clarify their targets to the UNFCCC.

Non-Energy Sectors

Other GHG-emitting sectors beyond energy are included in CPAT, and (per UNFCCC inventories), include:

- **Industrial processes and product use** – emissions predominately from the production of cement
- **Non-energy agriculture** – emissions of methane, mostly from ruminants (cattle, sheep) and rice farming
- **Energy agriculture** – the energy consumed to power agricultural facilities and other activities
- **Land use, land use Change and Forestry (LULUCF)** – emissions from land use change, notably the CO2 lost from deforestation
- **Waste** – emissions from waste in dumps, notably methane

[154] LULUCF is excluded for two main reasons. Firstly, there are very large disparities in measurement of LULUCF and they are not regularly reported by developing countries to the UNFCCC. Secondly, the inclusion of LULUCF can inhibit comparison of ambition in NDCs, especially of the central global mitigation challenge of energy sector decarbonization. For these reasons, methods for comparing mitigation ambition tend to exclude LULUCF. For a discussion of these issues, see: https://climateactiontracker.org/methodology/land-use-and-forestry/.

- **Fossil fuel extraction and distribution** – emissions from the production and transport of oil, natural gas, and coal.
- **Other** – a catch-all concept used by UNFCCC parties that can include, for example, emissions from the military

These sectors emit GHGs, such as CO_2, but in some cases the more problematic GHG is methane (CH_4). For example, globally, methane accounted for about 20 percent of global GHGs in 2020, of which about 40 percent was from fossil fuel extraction and distribution, about 40 percent from agriculture, and the remainder from waste and other sources (Parry and others, 2022). Predominately methane-emitting sectors (extractives, non-energy agriculture, and waste) and others (energy agriculture, industrial processes and product use as well as LULUCF) are modelled using separate approaches.

<u>Methane-emitting sectors</u>
Modelling of emissions from non-energy agriculture, waste, and extractives takes a slightly different approach from that of other sectors. The primary pollutant (methane) comes from leaks (in the case of extractives and waste) and production of tradable products (in the case of extractives)—this differs from other GHG emissions, which stem directly from combustion of fossil fuels. There are three steps taken in CPAT to model emissions from non-energy agriculture, extractives, and waste—note that non-energy agriculture is modelled separated for livestock and rice cultivation and extractives is modelled separately for coal and oil/natural gas.[155]

First, emissions factors in the base year are calculated, as emissions divided by production. Base year emissions come from UNFCCC data for non-energy agriculture and waste (given extensive cross-country data) and an average of the UNFCCC and IEA (2022b) for extractives (given the greater degree of underreporting in UNFCCC data suggested by satellite data for this sector).[156] Production is sourced from IEA and Enerdata energy balances for extractives, FAO for agriculture (FAOSTAT 2022), and the WB for waste (WB 2022b).

Second, emissions factors and production are projected forward in the BAU. Emissions factors assume an annual natural decline of 0.25 to 0.50 percent for all but coal,[157] reflecting autonomous technological improvements according to the EPA (2019) and FAOSTAT (2022). Production of agriculture (both livestock and rice) changes with GDP per capita and population, using elasticities of 0.15 and 0.9, respectively. Production of waste changes with real GDP, using elasticities that vary by country income-grouping to reflect that lower-income countries have higher elasticities (around 1.0 compared to 0.9 for advanced economies), partly due to a greater elasticity of waste-generating consumption to income. Production of oil, natural gas, and coal changes with global demand from the IEA BAU (assumed to be the 'Stated Policies Scenario', i.e., SPS). Total emissions in the BAU are calculated by multiplying production and emissions-intensity.

Third, the policy-induced changes to emissions-intensity are estimated using marginal abatement cost curves. Specifically, constant elasticity specifications are used (where the elasticity is negative). This implies that changes in emissions factors occur at a decreasing rate at higher levels of emissions prices, or, conversely, that the MACCs for cutting emissions rates are convex. The elasticity values are initially estimated at the country and sector-specific level (using MACCs from the US Environmental Protection Agency (EPA)) and then adjusted across all countries so that, at a global level, the percentage reductions in emissions intensity in response to pricing are approximately consistent with midrange estimates from recent studies.[158] This results in behavioral response functions that are specific to each country-sector pair (for example, coal in the United States). MACCs are assumed to have a zero intercept, which rules out the

[155] Emissions from other agricultural sources are assumed to change at the same rate as those of livestock and rice.
[156] See Crippa and others (2020); EPA (2019; Hoesly and others (2018); IEA (2022c); and Lauvaux and others (2022).Underreporting is largely due to methane leaks (especially by "super emitters") that are not well-captured under the current measurement framework. Leaks may also contribute to underreporting in the waste sector, although most research has focused on extractives.
[157] The emissions factor for coal is kept constant as a greater proportion of mining is conducted in underground mines, which have significantly greater emissions factors than open-pit mines. See Kholod and others (2020) for more.
[158] Specifically, three studies reported in UNEP (2021)—Harmsen and others (2019), IEA (2022a), and EPA (2019).

possibility of broader market failures due to firms not exploiting investments that are profitable in the absence of mitigation policy.

Lastly, production under the policy scenario is assumed to remain unchanged. This is due to the assumption that the policy is likely designed to be revenue-neutral to address competitiveness concerns for agriculture and extractives, and that there is no pass-through of taxes to waste consumers due to imperfect markets (e.g., government regulation). In general, demand responses are small and equal around 2 and 20 percent of the emissions reduction from a globally coordinated methane fee of USD 70 per ton of CO_2e (see Parry and others, 2022).

Land use, Land use Change and Forestry (LULUCF)
There is pervasive uncertainty about LULUCF emissions globally. However, LULUCF is conservatively assumed to be constant in the baseline for all countries (both net-sink and net-emitting countries), which is consistent with the approach taken for studies where data is missing (Forsell and others,2016).

Elasticities in non-energy sectors
CPAT includes estimates of baseline emissions for all sectors accounted for in emissions inventories submitted by countries to the UNFCCC per IPCC guidelines (2019). This includes: energy; industrial processes and product use; agriculture; land use, land use change, and forestry (LULUCF); waste; and other.

Emissions from these non-energy sectors are projected using simplified approaches:

- Industrial process emissions – which are principally CO_2 from cement and other industrial processes – are assumed to rise in proportion to energy CO_2 emissions in the mitigation module's industrial sector.
- LULUCF emissions – historical data for developed countries is taken from UNFCCC submissions.[159] Data is based on FAO estimates for developing countries (Tubiello and others 2021), though it should be noted there are conceptual ambiguities and significant uncertainties in such data.[160] LULULCF emissions are projected forward assuming a linear reduction during 2020-50 based on SSP5-8.5 scenario changes, which is a 2.5 percent reduction in net emissions per year in the period between 2020-50.[161] It should, however, be noted that LULUCF data is highly uncertain, with very large discrepancies across data sources and methodologies.[162] This uncertainty leads many models and modelers to exclude LULUCF, as do most cross-country analyses of decarbonization efforts.[163]
- Agriculture, waste, and other non-energy emissions – are projected using population and/or per capita income elasticities (Table AI.7), as described above.

[159] The latest data at the time of writing was available for year 2019.

[160] For example, FAO and UNFCCC inventory data results in significantly lower net emissions than those of other key datasets, such as the Global Carbon Budget (Friedlingstein and others 2021) and the most recent IPCC Working Group I report (IPCC 2021). For example, in 2019, combining data from UNFCCC (for Annex I countries) and FAO (for non-Annex I countries) implies global net LULUCF emissions of 0.85gtCO2. This is significantly lower than global estimates across three major 'bookkeeping' models of 6.6gtCO2 (Minx and others 2009), close to the discrepancy noted between national inventories and global approaches elsewhere (Grassi and others 2018). The main reason is that FAO and UNFCCC attribute indirect CO2 fluxes from environmental 'drivers' like CO2 fertilization (a major sink) to human activity, hence inventory approaches have lower net anthropogenic CO2 LULUCF emissions. However, country-level estimates from bookkeeping approaches remain too uncertain, and FAO data is preferable where consistency with UNFCCC data is required. Additionally, LULUCF emissions data is much more uncertain than from other sources due to complexities in carbon accounting and attribution.

[161] SSP5-8.5 is the 'worst case' scenario used by IPCC, though it should be noted the equivalent compound annual decline in emissions under SSP3-7.0 is slightly lower, at 2.3 percent between 2020-50.

[162] For example, there is a discrepancy of about 4 $gtCO_2e$ per year across global inventories, of which about 3.2 GtCO2 are due to conceptual differences in anthropogenic forest sink estimation (for example whether photosynthesis on managed land counts as an anthropogenic removal). See Grassi and others (2018).

[163] Including LULUCF in emissions estimates can also hide a lack of progress on the core challenge of decarbonizing energy consumption. For a discussion of this, and other reasons, see Climate Action Tracker – https://climateactiontracker.org/methodology/land-use-and-forestry/

Table A.I.7. Elasticities in non-energy sectors

Income and population elasticities	Agriculture	Waste	Other
Population elasticity	0.90	1.00	1.00
Per capita income elasticity	0.15	na	na

Source: IMF Staff

Annex II – Technical Details: Distribution Module

The distribution module's analysis is based on changes in energy prices under the climate mitigation policy scenario (relative to BAU) for a given year of interest (e.g., 2030), obtained from the mitigation module. These price changes are, then, used to estimate impacts on industries and households, accounting for net changes in consumption incidence from revenue recycling. The following sections describe key formulas, the estimation of indirect (household incidence) effects, revenue 'recycling' 'modes', as well as optional features in CPAT's distribution module.

Impacts on Industries (Direct and Indirect)

CPAT uses input-output tables sourced from the GTAP-10 database[164,165], which contains 2014 data for 65 sectors, including 59 non-energy sectors.[166] The energy intensities of non-energy production (e.g., food, clothing, and transport) $\bar{e_g}$ are estimated as follows:

$$(15) \quad e_g = f(I-A)^{-1}, \text{ f} \notin \text{g}$$

Where:

f	is a vector assigning an energy intensity coefficient to each non-energy sector
$(I-A)^{-1}$	is the Leontief inverse matrix (Leontief, 1986), i.e., the inverse of the technical coefficient matrix, which accounts for the proportionate increase in upstream inputs that are required to produce one unit of final demand in each sector
I	is the identity matrix
A	is a normalized matrix of technical coefficients based on inter-sectoral product flows from the GTAP database

The Leontief inverse of each non-energy sector (e.g., food and services) for each energy input e_g (e.g., coal, oil, electricity) is multiplied by the change in the energy input's price (from the mitigation module). This yields a first-order estimate of the average increase in input costs faced by firms in non-energy industries in percent of total input costs. This includes both the direct impact (from the change in the cost of energy inputs used in production) and the indirect impacts (from changes in non-energy intermediate input costs due to energy input cost changes, e.g., costs of fertilizers used in food production).

These impacts are shown for 59 non-energy sectors in the GTAP database. In the default case, it is assumed these increases in input costs are fully passed through to output prices faced by households (though this can be amended by the user – see discussion below). The input cost increases are, then, aggregated into 14 aggregated sectors with average intensities, e_g, and changes in output prices to facilitate household incidence analysis (see below). Groupings are determined based on energy intensity, as well as to match IEA sectoral definitions used in the CPAT mitigation module. Specifically, for each GTAP energy/fossil fuel sector, *f*, fossil fuel intensities, e_g in Eq. (15) of the 14 CPAT non-energy consumption categories, g, are a weighted average of the energy intensities of the respective non-energy GTAP sectors (using the GTAP IO tables' household final demand vectors as weights).

Impacts on Households (Direct and Indirect)

The burden on household consumption deciles d = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10} from higher output (i.e., end-user or retail) prices following a given climate mitigation policy is calculated as:

[164] See: https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx.

[165] The GTAP-10 database has several advantages. First, it is a consistent global database which harmonizes and scales data for 65 disaggregated sectors and 141 world regions to the year 2014. Such harmonized data improve comparability across country-specific results in CPAT. Additionally, GTAP-10 provides a more granular disaggregation of energy sectors than other global IO data with similar regional coverage (e.g., EORA).

[166] The 65 GTAP sectors include the following five fossil fuels: coal ("coa"), electricity ("ely"), oil ("oil"), natural gas ("gas", "gdt") and petroleum products ("p_c").

$$(16) \qquad \sum_g \pi_t^{dg} \cdot \rho_t^{dg}$$

Where:

g are (energy, non-energy) goods/services consumed by households,

π_t^{dg} is the share of decile *d*'s total consumption spent on good/service *g* at time *t*, and,

ρ_t^{dg} is the relative price increase for good/service *g* caused by the mitigation policy.

Data on household budget shares is obtained from national household budget surveys (HBSs). After the data is aggregated into the 8 energy and 14 non-energy CPAT-compatible good/service categories, households are grouped into population-weighted, per-capita consumption deciles. Budget shares are computed by dividing total consumption expenditure on each CPAT good/service category by each household's total consumption expenditure across all goods/services.

Direct impacts on households (changes in energy prices)

Sector-specific percent price changes in (fossil fuel) energy prices between the BAU and policy scenario (e.g., as induced by a carbon tax or fossil fuel subsidy reform) are obtained directly from the mitigation module. Calculating equation (16) above yields an estimate of the loss in consumption from price increases of energy products/fossil fuels (e.g., electricity, gasoline/diesel, natural gas, etc.) following the policy change (the 'direct' incidence effect). For example, for a good with a budget share of 2 percent of total household consumption, expression equation (16) implies that a 5 percent increase in said good's price will reduce decile d's consumption by 0.1 percentage points.

Indirect impacts (changes in non-energy good and service prices)

Price increases for other (i.e., non-energy) consumer goods/services (due to higher energy input prices) are calculated, assuming full pass-through of cost increases to consumer prices domestically (i.e., flat/perfectly elastic supply curves). In particular, non-fuel sector price increases are obtained as the sum-product of: i) each sector's intensity in each energy product (fossil fuel); and ii) the price increase of each energy product (fossil fuel) induced by the mitigation policy. Sectoral fossil fuel intensities are generally obtained from input-output/direct requirements matrices (see discussion on industry impacts above).

These are mapped to the CPAT non-energy/fossil fuel consumption good/service categories mentioned above to re-estimate expression (16). Summing the estimates across all non-energy/fossil fuel goods/services yields a measure of the change in consumption from price increases of non-energy/fossil fuel products (e.g., food, clothing, housing, etc.) following the introduction of a climate mitigation policy (i.e., the "indirect" incidence effect).

Summing the direct and indirect effects yields an estimate of the total effect on consumption. This can, then, be expressed in welfare terms (losses in consumer surplus) and adjusted in several ways (e.g., to account for imperfect pass-through of input costs to non-energy goods'/services' prices).

Revenue Recycling: Targeted Transfers

In CPAT, the user can choose to recycle a portion of the revenues via targeted transfers to households. These transfers can take the form of new cash transfers as well as scale-ups of existing social safety nets (e.g., social assistance, insurance, protection, contributory pensions, etc.).

These transfers can be 'targeted' in that they are sought to only apply to lower-income deciles defined by the user (e.g., the poorest 20 percent). However, government targeting of transfers is difficult (Coady and others 2004). CPAT allows the user to account for the two main forms of inefficiency in targeting: under-coverage (the proportion of the targeted population that does not receive a transfer, which is a type of false negative) and leakage (the proportion of the non-targeted population that does receive a transfer, a false positive). Accordingly, the four user-defined parameters are:

- the share of total revenues to be used for (new, existing) targeted and/or public spending transfers;
- the share of the population to receive the chosen transfer (starting from the bottom of the consumption distribution; $C_{jT} \leq p(T)\, C_{j,}$);
- the "coverage rate", i.e. the share of the population targeted and actually receiving the transfer; and

- the "leakage rate", i.e. the share of the untargeted population receiving the transfer.

These transfers are all modelled as direct, per capita payments and averaged by deciles. The amount of the targeted, per-capita transfer, T, for the targeted population, pop_T, is calculated by dividing total transferred revenues by the total eligible or "targeted" population in the year of interest y, such that:

$$(17) \qquad T^y = \frac{P_M^y}{pop_T^y}$$

Where the survey population (i.e., the sum of per capita population weights) is scaled to match projected national accounts population, *pop*, based on the IMF's latest World Economic Outlook vintage projections within CPAT, for the year of the distributional analysis, such that:

$$(18) \qquad pop_T^y = (\sum popw_T) * \theta_{pop}^y$$

where:

$$(19) \qquad \theta_{pop}^y = \frac{pop^y}{\sum popw}$$

New targeted transfers are conditional on per-capita consumption (user-defined choice above). Thus, the average per capita transfer, T_d^y, for decile d depends on the portion of the decile population, pop_T^{dy} , below the targeted consumption threshold (i.e., for which $C_{jT} \leq p(T)\ C_j$) such that:

$$(20) \qquad T_d^y = T^y * \frac{\sum pop_T^{dy}}{\sum pop^{dy}}$$

<u>Revenue recycling: Current Spending</u>
Countries could use a portion of revenues from climate mitigation policies for general government expenditures (also known as 'current spending'). Accordingly, if the user allocates a portion of revenues to current spending, they can select that these expenditures be allocated to: social assistance, insurance, protection, labor support, other social assistance, cash transfers, contributory pensions, public works, in-kind benefits, or cash transfers. These types of recycling modes are based on the Atlas of Social Protection Indicators of Resilience and Equity (ASPIRE) dataset[167].

It is assumed that these schemes are scaled proportionately by ΔA for each protection scheme *a*. Following equation (20) above, CPAT defines:

$$(21) \qquad \Delta A_a^y = \frac{P_M^y}{A_a^y}$$

where A_a^y is the inflation-adjusted total government spending on protection scheme *a,* in the year of interest y. To calculate total government spending, CPAT first multiplies per-capita quintile transfer amounts by a fifth of the population pop_y in the year of interest y, to arrive at total spending by quintile, which is, then, summed up. CPAT arrives at average decile transfers assuming every two deciles receive the same amount (in per capita terms) as their corresponding quintile (e.g., deciles 1 and 2 receive the per-capita transfer of quintile 1 and so on). The approach described here (in tandem with the targeting parameters listed above) also applies when users choose to recycle climate mitigation policy revenues via existing (as opposed to new) targeted transfers.

<u>Revenue Recycling: Infrastructure Investment</u>
In CPAT, users can choose to recycle a portion of the mitigation policy revenues through infrastructure investment. The user can choose to increase access to: water, sanitation, electricity, information & communication technology (ICT), public transport or average infrastructure access across the aforementioned types. Increasing access to each of the types mentioned above could have varying impacts across deciles, depending on the country in question.

[167] See: http://pubdocs.worldbank.org/en/531411485449033265/ASPIRE-expenditure-program-documentation.xlsx

The portion of the decile population, pop_T^{dy}, receiving the transfer, per Equation (20) is calculated based on the weighted share of households in decile d who have access to infrastructure category *i*, F^{di}, such that:

$$(22) \quad pop_{Ti}^{dy} = \sum_{d=1}^{10} pop^{dy} * (1 - \mathrm{F}^{di})$$

Transfers are, hence, received only by those households without initial access to infrastructure type i (with infrastructure access shares for each decile calculated from the HBS data), F_j^i.

Revenue Recycling: Personal Income Tax Reductions

The distributional effects of climate policy (CP) revenue recycling via personal income tax (PIT) reductions depend on the baseline PIT liabilities of individuals at different segments of the income distribution. Broadly speaking, these liabilities are a function of two components: taxable (i.e., "gross") income and PIT schedules. To circumvent the modeling of (often complex) PIT systems around the world, CPAT, instead, obtains this information via data on the share of each (disposable, market) income decile's PIT liabilities in economy-wide PIT liabilities.[168]

Decile-specific shares in aggregate PIT liabilities are based on nominal PIT liability data by decile, which is collected from two main sources:

- First, CPAT relies on the latest vintage(s) of the Luxembourg Income Study (LIS)[169]. The LIS contains nationally representative household (HH) survey data on income, demographics, and labor market characteristics. Using the LIS, disposable income[170] decile-specific, PIT liabilities are, thus, obtained as the HH-weighted sum of the "hxitax" variable[171].
- Second, CPAT also obtains similar data from the latest vintage of the Commitment to Equity (CEQ) "Standard Indicators" database[172] for each country. This database contains information on the incidence (in percent of total market income) of "direct taxes" paid by market income[173] decile. From this data, CPAT obtains the decile-specific sum of direct taxes paid.

Across both data sources, decile-specific shares of income/direct taxes paid are calculated as the ratios of the decile-specific total tax liabilities to the sum of all tax liabilities across deciles.[174] Taking income/direct taxes as a proxy for PIT liability, the above results in a database of PIT liability shares at the country-year-decile level.[175] For the purposes of estimation within the CPAT distribution module, decile-specific PIT liability shares in economy-wide PIT paid are assumed to be constant over time.

Economy-wide PIT paid is, subsequently, calibrated to equal the product of: i) average PIT-to-GDP ratio[176] during the period 2010-2019[177]; and ii) GDP in the year of interest for the distributional effects analysis, y.

[168] This information should already account for elements such as, for example, the decile-specific incidence of non-standard PIT regimes, informality, and tax evasion/avoidance, without the need for additional assumptions in this regard.

[169] See: https://www.lisdatacenter.org/.

[170] The LIS does not, generally, collect consumption information, making it difficult to obtain income taxes paid by household (weighted) per-capita consumption decile.

[171] This variable contains annual "income taxes" paid by households in the survey year and is available for 26 countries (across all World Bank income groups). The surveys mostly date from the period 2010-2019, except for data for the Dominican Republic (2007), Romania (1997) and Sweden (2005).

[172] The CEQ "Standard Indicators" database contains data on 42 countries (across all World Bank income groups), based on CEQ analyses covering the period 2009-2017. See: https://commitmentoequity.org/indicators.php

[173] Similar to the LIS data described above, the CEQ database does not contain data at the consumption decile level.

[174] CPAT complements the LIS and CEQ data discussed here with information on PIT paid by household per-capita consumption decile from the household budget surveys discussed above. However, said information is only available for a few countries (Egypt, Pakistan, Philippines, and Ukraine).

[175] Missing country observations are replaced with the mean (or median, should the user choose to report median distributional effects in CPAT) of the country's World Bank income or regional (depending on what the user selects in CPAT) group. See: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

[176] Data on annual, country-level PIT-to-GDP ratios is obtained from the IMF's World Revenue Longitudinal Database (WoRLD). See: https://data.imf.org/?sk=77413f1d-1525-450a-a23a-47aeed40fe78.

[177] The analysis excludes countries with missing 2010-2019 average PIT-to-GDP ratios. Most of these countries (e.g., the Bahamas, Brunei, Oman, Qatar, United Arab Emirates) do not have a PIT regime in place.

Analytically:

$$(23) \qquad L_{dcy} = s_{dc} * AVG\_PIT\_GDP_c * RGDP_{cy} \text{ and } l_{dcy} = L_{dcy}/P_{dcy}$$

Where:

L_{dcy} and l_{dcy} stands for the total and per-capita PIT liabilities of decile d in country c and analysis year y.

$AVG\_PIT\_GDP_c$ is the 2010-2019 average PIT-to-GDP ratio for country c (assumed to be constant over time),

$RGDP_{cy}$ is the real GDP in constant 2021 local currency units (LCU) in country c and analysis year y and

P_{dcy} is the total population of decile d in country c and analysis year y. P_{dcy} is calibrated to national population in country c and analysis year y, based on the country-specific population distributions obtained from household budget surveys (HBSs) as part of the data requirements for the CPAT consumption incidence calculations.

s_{dcy} is the share of PIT liability of decile d in country c and analysis year y, proxied by data on direct or individual income taxes as described above.

The resulting estimates are merged with each country's, decile-level HBS data for the overall sample[178], assuming a 1:1 correspondence between the LIS/disposable income and CEQ/market income deciles and the consumption deciles from the various HBSs. In cases, where LIS and CEQ country coverage overlaps[179], CPAT prioritizes the source which covers the latest available year of data[180]. If the user chooses to recycle a percentage of CP revenues towards "labor tax reductions", the CPAT Distribution Module estimates resulting per-capita decile-specific gains (in real 2021 LCU) under three (mutually exclusive) PIT liability reduction scenarios:

Impacts depend on the users' choice for how to reduce PIT liabilities, for which the options are: targeted exemptions, personal allowance, and proportional compensation.

Targeted Exemption. Under this scenario, selected HH consumption deciles gain the baseline amount of PIT they pay, conditional on available CP revenues. In other words, the allocation of CP revenues would be such that said deciles would not be liable for PIT. In this case, the per-capita LCU gain g for (HH per-capita consumption) decile d in country c and analysis year y can be written as:

$$(24) \qquad g_{dcy\_TE} = l_{dcy}\mathbb{I}[d = exempt]\mathbb{I}[0 \leq remaining\ CT\ revenues\ \leq l_{dcy}]$$

Where:

l_{dcy} stands for the per-capita PIT liability of decile d in country c and analysis year y.

$\mathbb{I}[d = exempt]$ is an indicator function denoting that decile d has been selected as the decile to be fully exempt from PIT via the use of CP revenues.

$\mathbb{I}[0 \leq remaining\ CT\ revenues\ \leq l_{dy}]$ is another indicator function denoting that decile d will only benefit from a full PIT exemption of an amount up to (or less than) l_{dcy}, provided that a non-zero amount of CP revenues is available for said purpose.[181]

[178] Given the nature of the underlying data and calculations, it was not possible to estimate PIT liabilities by type of sub-sample (e.g., urban vs. rural) and statistic (e.g., median, p25, p75). However, median income/regional group averages will be used for countries that lack decile-specific PIT liability shares, if CPAT users choose to show median distributional effects in CPAT (for all remaining countries median liabilities are assumed to equal mean liabilities).

[179] This is the case for the following countries: Brazil, Colombia, Dominican Republic, Peru, Russia, South Africa and the United States.

[180] Except for the Dominican Republic, CPAT prioritizes LIS over CEQ, due to the former's coverage of more recent data. LIS is also preferable, owing to its inclusion of data at the disposable income decile level. This is because disposable income-level data is a better proxy for consumption (and, thus, welfare) relative to the market income decile-level data in CEQ. By virtue of this, the LIS deciles are also more comparable to the HBS deciles that CPAT uses when estimating consumption incidence effects.

[181] It should, thus, be noted that, even if CP revenues are not enough to fully offset the PIT liability of decile d under this scenario, the Distribution Module will still allocate any remaining CP revenue amounts starting from this decile (and moving upwards onto any remaining deciles), provided that these amounts are available to be allocated.

Personal Allowance. Under this scenario, PIT liabilities are (in absolute terms) uniformly reduced across the PIT-paying population, similar to a per-capita lump-sum transfer to the working population. The respective (equal, per-capita) gains are calculated by dividing the proportion of CP revenues used for PIT reductions by the sum of all individuals in the country. The calculated amount is the maximum available transfer for PIT reduction purposes. Hence, the per-capita LCU gain g for (HH per-capita consumption) decile d in country c and analysis year y can be written as:

$$g_{dcy\_PE} = \min\{l_{dcy}, r_{cy}\} \quad (25)$$

Where:

l_{dcy} stands for the per-capita PIT liability of decile d in country c and analysis year y. Additionally, r_{cy} is the ratio of all available CT revenues to the sum of all individuals in the country and represents the maximum possible mean per-capita gain of a given decile d. Decile d is, hence, guaranteed l_{dcy} provided that $l_{dcy} < r_{cy}$. Finally, r_{cy} is parametrized such that it reflects use of all CP revenues made available for PIT liability reductions across deciles. Specifically, any remaining revenues are equally divided across all individuals in the country and paid out as additional gains under this reform scenario.[182]

Proportional Compensation: Under this scenario, each (HH consumption) decile receives an average per-capita gain that increases with the HH's baseline PIT liability. In other words, the more PIT a decile pays, the higher the gain. Therefore, the per-capita LCU gain g for (HH per-capita consumption) decile d in country c and analysis year y can be written as:

$$g_{dcy\_PC} = l_{dcy} * f_{cy} \quad (26)$$

Where:

l_{dcy} stands for the per-capita PIT liability of decile d in country c and analysis year y. Additionally, f_{cy} is a scalar representing the LCU gain from CP revenue recycling per LCU of baseline PIT paid. This is, in turn, calculated as the total LCU amount of available CP revenues divided by the total LCU amount of PIT paid across all deciles. For instance, a value of 0.5 would be interpreted as each HH consumption decile gaining 0.5 LCUs from CP revenue recycling for each LCU of baseline PIT it pays.[183]

The methodology described here is subject to a series of assumptions and caveats:

- First, the PIT liability calculations assume away any estimates based on actual fiscal regime data (e.g., detailed modeling of tax credits, surtaxes, and potential - sector-specific - deductions, etc.).
- Second, the PIT liability share calculations assume that the household survey data available via the LIS and CEQ accurately capture the entirety of PIT paid across the income distribution.
- Third, any gains from PIT reductions are assumed to be distributed equally across all population sub-groups (i.e., working and non-working individuals, adults and children, men and women, etc.).
- Fourth, the data-generating process outlined above assumes perfect correspondence between consumption and income deciles. Fifth, the revenue recycling calculations assume no changes in PIT payments/compliance in response to the climate mitigation policy.
- Finally, the calculations presented above remain agnostic as to the size and distribution of gains from PIT liability reductions for the urban vs. rural sub-samples in CPAT. CPAT simply scales any estimated gains for the overall sample of household by the share of urban and rural population in total population, thus yielding the gains for the urban and rural sub-samples respectively.

[182] Since this scenario resembles a lump-sum, per-capita transfer to the working population, gains are likely to be, by default, progressively distributed. This is because transfers tend to represent a larger proportion of poorer households' incomes.

[183] In general (depending on the distribution and magnitudes of decile-specific PIT liability shares), this scenario results in a relatively more regressive effect of CP revenue recycling across HH consumption deciles.

User Options

The user can customize the distribution module in several ways.

Behavioral and structural change-adjusted incidence
This adjustment scales down overall consumer price increases relative to the policy's mitigation effect, thus relaxing the cost-push assumption of the distribution module. The mitigation module provides estimates of economy-wide GHG emissions reductions and revenues from climate mitigation over time. As noted above, the distribution module is based on IO data. This assumes fixed technical coefficients and, thus, full price pass-through, such that the estimated incidence is to be understood as an absolute upper bound, or short-term, estimate.

CPAT provides the user with an approximate measure of the extent to which consumption effects would decrease if behavioral responses and structural change were considered. To do this, for the (future) year of interest, CPAT compares the climate mitigation policy revenue estimates from the mitigation module with the revenues of the distribution module (based in HBS data), generating the proportion of revenues raised after and before considering behavioral/structural responses:

Let the economy-wide policy burden, or total mitigation policy revenues, estimated in the mitigation module be P_M^y for year y, and in the distribution module be P_D^y ($P_M^y < P_D^y$), where:

$$\text{(27)} \qquad \mathrm{P}_D = \sum_j \mathrm{p_j} * C_j$$

represents the total expected revenues based on representative HBS consumption data C_j. CPAT scales P_D to match national accounts data in the year of interest y (2024≤ y ≤ 2030), such that:

$$\text{(28)} \qquad P_D^y = \mathrm{P}_D * \frac{GDP^y * \theta_c}{\sum C_j}$$

where GDP^y represents the expected GDP in the year of interest for the distributional analysis and θ_c represents the final consumption expenditure to GDP ratio for the latest available year from the World Bank's World Development Indicators (WDI) database.[184] Then, the downward adjustment factor for the incidence on households, p_{Adj} is computed as:

$$\text{(29)} \qquad \mathrm{p}_{Adj} = \frac{P_D^y - P_M^y}{P_D^y} \;, \; P_M^y < P_D^y$$

The adjustment factor p_{Adj} is applied as a multiplicative scalar across all (household consumption) deciles.

Decile-specific price elasticities of demand
CPAT allows the user to model short-term adjustments on the demand side alone, using decile-, country-, and consumption category-specific price elasticities of demand based on USDA data[185]. The price elasticities provided are by country and consumption category (COICOP) for high-, middle- and low-income countries.

Based on standard classifications (e.g., COICOP), CPAT maps the elasticities to distribution module consumption categories. CPAT, then, uses the countries' reported elasticities for the middle deciles. For the remaining deciles, CPAT assumes that the upper and lower deciles' elasticities will deviate from said middle-decile elasticity by the same proportion as the elasticities for low- and high-income countries deviate from those of middle-income countries. This assumption is made separately for each consumption category. Following the same approach as in the mitigation module (i.e., assumed constant elasticity of substitution or CES utility functional forms), the country-decile-specific price elasticity of demand for consumption category g, ${\epsilon_{use}}^g$ modifies the budget share for each product, C_j^g , as follows:

$$\text{(30)} \qquad C_j^g * \left(\frac{p_t}{p_{t-1}}\right)^{\epsilon_{use}}$$

[184] WDI 2020: 'Households and NPISHs final consumption expenditure' (% of GDP; NE.CON.PRVT.ZS)
[185] See: https://data.ers.usda.gov/reports.aspx?ID=17825

Imperfect pass-through

CPAT also provides the user with the possibility of allowing producers to absorb, i.e., not “pass through”, part of the mitigation policy-induced price increase. Coefficients γ_g ($\gamma_g \leq 1$) based on Ganapati and others (2020), Neuhoff & Ritz (2019) and Abdallah and others (2020) are applied to the climate mitigation (effective tax) rate *t* for sector *g*, expressed as the price increase post- vs. pre-climate mitigation policy reform, such that the downward-adjusted energy price change $\mathrm{t}^*_{\mathrm{fg}}$ can be expressed as:

$$(31) \qquad \mathrm{t}^*_{\mathrm{fg}} = \mathrm{t}_{\mathrm{fg}} * \gamma_g$$

Emissions-based adjustment of sectoral price changes

As described above, the (consumption) incidence of goods’ and services’ price changes on households is based on GTAP-related energy product/fossil fuel-sector Leontief coefficients. Multiplying the Leontief with the respective fuel’s price change, one obtains ‘indirect’ consumer price changes. This multiplication implicitly introduces a price assumption to the GTAP monetary flow of energy. On the other hand, based on observed fuel prices (US$/unit of fuel in a base year), the mitigation module estimates expected fuel price changes. Thus, this calculation assumes a corresponding energy flow. However, this energy flow might not necessarily match the observed energy flow by fuel and sector (which CPAT takes from IEA data).

To correct for this potential imbalance, CPAT allows the user to adjust consumer price incidence by theoretical, “time-zero” revenue flows from the modeled climate mitigation policy. This means that CPAT calculates the revenues that would have been raised if no price-induced adjustments had taken place (hence the term “time-zero” revenues). These theoretical revenue streams are calculated by fuel and CPAT sector. The final demand portion of this price incidence on the economy (usually around 60%, as the remainder is accounted for by goods which are exported or consumed by the government and fixed capital formation) is equivalent to the static consumption incidence, which should be reflected in the analysis. CPAT, thus, allows the user to scale the initially estimated incidence effects to this level. If this option is selected, additional estimates are, subsequently, calculated incorporating said adjustment.

Cooking-fuel adjusted incidence effects

For selected deciles (starting from the bottom one), CPAT provides the user with the option to exclude the primary fossil fuel used for cooking from the simulated mitigation policy (and consumption incidence analysis). From a policymaking standpoint, this option is to be understood as a rebate to limit perverse incentives for switching into biomass for cooking in response to the climate mitigation policy. In other words, it is, e.g., assumed that the household will pay the (carbon) tax/price when buying the fuel but will receive a compensatory transfer for its cooking needs. Primary fossil fuels used for cooking are identified for each country based on the World Health Organization (WHO) Household Energy Database[186].

[186] https://www.who.int/airpollution/data/household-energy-database/en/

Annex III – Technical Details: Co-Benefits Modules (Air Pollution & Transport)

Air pollution co-benefits

Emissions factors for local pollutants
Emissions factors for local pollutants are sourced from IIASA. The baseline GAINS scenario is the ECLIPSE_V5a_CLE_base and it provides data for 89 countries (regional averages are used for others). This dataset was created in June 2015 and covers emissions from 1990 to 2050 in five-year intervals, with the assumption that emissions factors generally decrease as higher-quality fuel and better control technologies are introduced. The emissions factors were grouped to reflect CPAT sectors and fuels, as described in Wagner and others (2020).

Deaths and morbidity from local air pollution—concentrations to health outcomes and economic costs
The main health outcomes calculated are premature mortality attributed to pollution from fuel use and lost disability-adjusted life years (DALYs). Baseline data on air pollution and disease levels come from a variety of sources (WHO; GBD, 2019).

For PM2.5, CPAT uses an approach based on GBD (2019) to model the relationship between pollutant concentrations and health outcomes. A relative risk (RR) curve, which is an estimate of the increase in the likelihood of an adverse health event caused by an increase in exposure to harmful pollutants, determines the air pollution-attributable fraction in the burden of diseases. The RR curves differentiate impacts among age groups (neonatal, post-neonatal, under-15 years old, 15 to 64 years, and 65 years or older) and diseases (e.g., chronic obstructive pulmonary disease, stroke, and ischemic heart disease). Ozone impacts use a similar methodology with RR functions based on Turner and others (2016). Adjustments are made when multiple risk factors impact the same outcome to avoid double counting and omitting any non-linearity in relationships between exposure and health outcomes.

The health impacts from household air pollution (HAP), defined as the use of solid fuels for cooking, are also modelled. The reason to include HAP is twofold: i) the GBD (2019) framework requires a joint estimation of ambient and household pollution; and ii) higher fossil fuel prices could lead to households using more solid fuels (e.g., biomass). Therefore, HAP is related to energy pricing policies. Note that when HAP is high compared to ambient pollution, the health gains from reducing ambient pollution will be much smaller than when HAP is low or zero. As a result, for countries with high HAP, the health impacts from carbon pricing can be small.

The economic costs of outdoor air pollution (i.e., externalities) come from a variety of adverse health outcomes. A few examples include:

- *Work absenteeism*, which leads to wage losses, worker replacement costs, and productivity declines for other workers that depend on the absent labor. Work absenteeism is modelled using approaches from Ostro (1987) and Holland (2014) with baseline levels of absenteeism from OECD (2020) and WHO (2019).
- *Market output losses due to working years lost from mortality and years with disability*. CPAT uses a model based on Pandey and others (2021), but without adjustments for rural vs. urban samples. Mortality is assumed to occur up to 20 years from the time of exposure to elevated levels of pollutants.
- *Health expenditures that are attributed to pollution*. Total costs due to pollution are a percentage of total costs, based on the percentage of DALYs caused by fuel-related pollution (similar to Preker and others, 2016) and expected future health care costs at the country level from IHME (2020).

Road transport co-benefits

Vehicle kilometers traveled (VKT) and road transport co-benefits

Road transport externalities are closely related to the level of VKT. Baseline values for VKT and road maintenance come from the World Road Statistics (IRF 2021), congestion-related data on free-flowing speeds and actual speeds from TomTom, and driving-related fatalities from WRS, UNECE, and OECD.

VKT and the externalities are projected forward using country-specific data, applying short- and long-run elasticities with respect to prices and macro-economic indicators. Equation (32) provides the regression run to estimate elasticities for all outcome variables (i.e., VKT and each externality), with the *within* estimator from a static fixed-effects equation representing shorter-run effects, and the *between* estimator providing estimates of long-run effects following Burke and Nishitateno (2015). Separate regressions were run for each outcome variable.

$$\ln(Y_{c,t}) = \propto + \beta \ln(p_{c,t}) + \gamma X_{c,t} + \mu_t + \mu_c + \epsilon_{c,t} \quad (32)$$

Where:

Y	outcome variable (VKT, congestion, fatalities, road maintenance)
p	gasoline price
X	a vector of covariates including GDP per capita and population
μ	country and year fixed effects
c	country
t	year

The average resulting short-run (resp. long-run) elasticity (with respect to fuel prices) for VKT is -0.28 (resp. -0.56), for congestion it is -0.34 (resp. -0.81), and for road accident fatalities it is -0.61 (resp. -0.44). The road damage short-run elasticity (with respect to diesel prices) is not statistically significant and its long-run elasticity is on average -0.44, results which are in line with the literature.

Annex IV – CPAT Applications

Table A.IV.1 Selected IMF Applications of the Climate Policy Assessment Tool (CPAT)

Coverage	Year	Publication	Title
Country analysis			
Belgium	2023	SIP	Fiscal Policy Options to Accelerate Emissions Reductions in Belgium
Chile	2023	TAR	Chile: An Evaluation of Improved Green Tax Options
Peru	2023	SR	Peru: 2023 Article IV Consultation
Madagascar	2022	TAR	Republic of Madagascar: Climate Macroeconomic Assessment Program (CMAP)
Philippines	2022	SIP	Philippines: Selected Issues
Thailand	2022	SIP	Thailand: Selected Issues
Canada	2021	SIP	Canada: Selected Issues
Finland	2021	WP	Fiscal Policies for Achieving Finland's Emission Neutrality Target
Germany	2021	WP	Scaling up Climate Mitigation Policy in Germany
Korea	2021	SIP	Republic of Korea: Selected Issues
Mexico	2021	WP	A Comprehensive Climate Mitigation Strategy for Mexico
Netherlands	2021	WP	A Comprehensive Greenhouse Gas Mitigation Strategy for The Netherlands
China	2020	BC	Evaluating Policies to Implement the Paris Agreement: Application to China
Denmark	2020	WP	Climate Mitigation Policy in Denmark: A Prototype for Other Countries
India	2019	BC	Reforming Energy Policy in India: Assessing the Options
Canada	2017	JA	Canada's Carbon Price Floor
China	2016	WP	Climate Mitigation in China: Which Policies Are Most Effective?
Regional analysis			
Middle East	2023	DP	A Low-Carbon Future for the Middle East and Central Asia: What are the Options?
Latin America	2023	REO	Regional Economic Outlook for Latin America and the Caribbean, October 2021
Europe	2022	WP	Targeted, Implementable, and Practical Energy Relief Measures for Households in Europe
Europe	2022	WP	Surging Energy Prices in Europe in the Aftermath of the War
Global & thematic analysis			
All countries	2022	SCN	Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade
G20	2022	SCN	Carbon Taxes or Emissions Trading Systems?: Instrument Choice and Design
G20	2022	WP	A Framework for Comparing Climate Mitigation Policies Across Countries
G20	2022	FM	Fiscal Monitor: Fiscal Policy from Pandemic to War
Various	2022	SCN	How to Cut Methane Emissions
All countries	2021	SCN	Not Yet on Track to Net Zero: The Urgent Need for Greater Ambition and Policy Action
G20	2021	SCN	Proposal for an International Carbon Price Floor Among Large Emitters
191 countries	2021	WP	Still Not Getting Energy Prices Right: An Update of Fossil Fuel Subsidies
G20	2021	JA	Mitigation Policies for the Paris Agreement: An Assessment for G20 Countries
135 countries	2019	BP	Fiscal Policies for Paris Climate Strategies
G20	2019	FM	Fiscal Monitor: How to Mitigate Climate Change

Source: IMF staff.
Note: SIP = Selected Issues Paper, TAR = Technical Assistance Report, SR = Article IV Staff Report, WP = Working paper, DP = Departmental Paper, FM = Fiscal Monitor, REO = Regional Economic Outlook, SCN = IMF Staff Climate Note, BP = Board Paper, BC = Book Chapter, JA = Journal Article.

References

Abdallah, Chadi, David Coady, and Nghia-Piotr Le. 2020. "The Time Is Right! Reforming Fuel Product Pricing Under Low Oil Prices." Special Series on COVID-19, IMF, Washington, DC, . https://www.imf.org/-/media/Files/Publications/covid19-special-notes/enspecial-series-on-covid19the-time-is-right-reforming-fuel-product-pricing-under-low-oil-prices.ashx.

Acworth, William, Mariza Montes de Oca, Anatole Boute, Carlotta Piantieri, and Felix Christian Matthes. 2020. "Emissions Trading in Regulated Electricity Markets." Climate Policy 20 (1): 60–70. https://doi.org/10.1080/14693062.2019.1682491.

Andersson, J.J. 2019. "Carbon Taxes and CO2 Emissions: Sweden as a Case Study." American Economic Journal: Economic Policy 11 (4): 1–30. https://www.aeaweb.org/articles?id=10.1257/pol.20170144.

Anderson, Gareth, Jiayi Ma, Tokhir N Mirzoev, Ling Zhu, and Karlygash Zhunussova. 2022. "A Low-Carbon Future for the Middle East and Central Asia: What Are the Options?" Departmental Paper No 2022/018.https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2022/10/28/A-Low-Carbon-Future-for-the-Middle-East-and-Central-Asia-What-are-the-Options-523812.

Angrist, J. D., & Pischke, J. S. 2009. "Mostly harmless econometrics: An Empiricist's Companion". Princeton University Press.

Aldy, Joseph E., and Sarah Armitage. 2020. "Cost-Effectiveness Implications of Carbon Price Certainty." AEA Papers and Proceedings 110 (May): 113–18. https://doi.org/10.1257/pandp.20201083.

Alonso, Cristian, and Joey Kilpatrick. 2022. "The Distributional Impact of a Carbon Tax in Asia and the Pacific." IMF Working Papers 2022 (116). https://doi.org/10.5089/9798400212383.001.

Aleluia Reis, Lara. 2020. "Down-Scaling FASST(R) to Country Level."

Apte, Joshua, Emilie Bombrun, Julian Marshall, and William Nazaroff. 2012. "Global Intraurban Intake Fractions for Primary Air Pollutants from Vehicles and Other Distributed Sources." Environmental Science and Technology 46 (6): 3415–23. https://doi.org/10.1021/es204021h.

Ari, Anil, Nicolas Arregui, Simon Black, Oya Celasun, Dora Iakova, Victor Mylonas, Ian Parry, Iulia Teodoru, and Karlygash Zhunussova. 2022. "Surging Energy Prices in Europe in the Aftermath of the War: How to Support the Vulnerable and Speed up the Transition Away from Fossil Fuels." IMF Working Papers No. 2022/152, https://www.imf.org/en/Publications/WP/Issues/2022/07/28/Surging-Energy-Prices-in-Europe-in-the-Aftermath-of-the-War-How-to-Support-the-Vulnerable-521457.

Arregui, N., Celasun, O., Iakova, D., Mineshima, A., Mylonas, V., Toscani, F., Wong, Y., Zeng, L., & Zhou, J. (2022). Targeted, Implementable, and Practical Energy Relief Measures for Households in Europe. IMF Working Papers, 2022/262, https://www.imf.org/en/Publications/WP/Issues/2022/12/17/Targeted-Implementable-and-Practical-Energy-Relief-Measures-for-Households-in-Europe-526980

Batini, Nicoletta, Luc Eyraud, Lorenzo Forni, and Anke Weber. 2014. "Fiscal Multipliers: Size, Determinants, and Use in Macroeconomic Projections." Washington D.C.: IMF. https://www.imf.org/en/Publications/TNM/Issues/2016/12/31/Fiscal-Multipliers-Size-Determinants-and-Use-in-Macroeconomic-Projections-41784.

Batini, Nicoletta, Ian Parry, and Philippe Wingender. "Climate Mitigation Policy in Denmark: A Prototype for Other Countries." Working Paper No. 2020/235, 2020. https://www.imf.org/en/Publications/WP/Issues/2020/11/12/Climate-Mitigation-Policy-in-Denmark-A-Prototype-for-Other-Countries-49882.

Batini, Nicoletta, Simon Black, Oana Luca, and Ian Parry. 2021. "A Comprehensive Greenhouse Gas Mitigation Strategy for The Netherlands." IMF Working Papers, no. 2021/223 (August): 40.

https://www.imf.org/en/Publications/WP/Issues/2021/08/20/A-Comprehensive-Greenhouse-Gas-Mitigation-Strategy-for-The-Netherlands-464339.

Beiser-McGrath, L. F., and Bernauer, T. 2019. Could revenue recycling make effective carbon taxation politically feasible?. *Science advances*, *5*(9), eaax3323.

Bento, Antonio M., Mark R. Jacobsen, and Antung A. Liu. 2018. "Environmental Policy in the Presence of an Informal Sector." Journal of Environmental Economics and Management 90: 61–77. https://doi.org/10.1016/j.jeem.2018.03.011.

Black, Simon, and Ian Parry. 2020. "Implications of the Global Economic Crisis for Carbon Pricing: A Quantitative Assessment for Coalition Member Countries." https://www.financeministersforclimate.org/sites/cape/files/inline-files/IMF-WB%20Coalition%20Note%20-%20Implications%20of%20the%20Global%20Economic%20Crisis%20for%20Carbon%20Pricing.pdf.

Black, Simon, Koralai Kirabaeva, Ian Parry, Mehdi Raissi, and Karlygash Zhunussova. 2021a. "A Comprehensive Climate Mitigation Strategy for Mexico." IMF Working Paper No. 2021/246. https://www.imf.org/en/Publications/WP/Issues/2021/08/20/A-Comprehensive-Greenhouse-Gas-Mitigation-Strategy-for-The-Netherlands-464339.

Black, Simon, Ruo Chen, Aiko Mineshima, Victor Mylonas, Ian Parry, and Dinar Prihardini. 2021c. "Scaling up Climate Mitigation Policy in Germany." Working Paper No. 2021/241. https://www.imf.org/en/Publications/WP/Issues/2021/09/27/Scaling-up-Climate-Mitigation-Policy-in-Germany-465421.

Black, Simon, Ian Parry, James Roaf, and Karlygash Zhunussova. 2021c. "Not Yet on Track to Net Zero: The Urgent Need for Greater Ambition and Policy Action to Achieve Paris Temperature Goals," IMF Staff Climate Notes, no. 2021/005: 30. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2021/10/29/Not-Yet-on-Track-to-Net-Zero-The-Urgent-Need-for-Greater-Ambition-and-Policy-Action-to-494808.

Black, Simon, Danielle Minnett, Ian Parry, James Roaf, and Karlygash Zhunussova. 2022a. "A Framework for Comparing Climate Mitigation Policies Across Countries." IMF Working Papers, Working Paper No. 2022/254, https://www.imf.org/en/Publications/WP/Issues/2022/12/16/A-Framework-for-Comparing-Climate-Mitigation-Policies-Across-Countries-527049.

Black, Simon, Jean Chateau, Florence Jaumotte, Ian Parry, Gregor Schwerhoff, Sneha Thube, and Karlygash Zhunussova. 2022b. "Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade." IMF Staff Climate Note No 2022/010, 39. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/10/31/Getting-on-Track-to-Net-Zero-Accelerating-a-Global-Just-Transition-in-This-Decade-525242.

Böhringer, Christoph, Sonja Peterson, Thomas F. Rutherford, Jan Schneider, and Malte Winkler. 2021. "Climate Policies after Paris: Pledge, Trade and Recycle: Insights from the 36th Energy Modeling Forum Study (EMF36)." Energy Economics 103 (November): 105471. https://doi.org/10.1016/j.eneco.2021.105471.

Bretscher, Lucas, and Elise Grieg. 2020. "Exiting the Fossil World: The Effects of Fuel Taxation in the UK." Economics Working Paper Series, Center of Economic Research at ETH Zurich, https://doi.org/10.3929/ETHZ-B-000410578.

Burke, Paul J., and Hua Liao. 2015. "Is the Price Elasticity of Demand for Coal in China Increasing?" *China Economic Review* 36 : 309–22. https://www.sciencedirect.com/science/article/pii/S1043951X1500125X.

Burke, Paul J., and Zsuzsanna Csereklyei. 2016. "Understanding the Energy-GDP Elasticity: A Sectoral Approach." Energy Economics 58: 199–210. https://doi.org/10.1016/j.eneco.2016.07.004.

Burns, Andrew, Benoit Campagne, Charl Jooste, David Stephan, and Thi Thanh Bui. 2019. "The World Bank Macro-Fiscal Model: Technical Description". World Bank, Washington, DC. https://doi.org/10.1596/1813-9450-8965.

Byers, Logan, Johannes Friedrich, Roman Hennig, Aaron Kressig, Colin Mccormick, and Laura Malaguzzi Valeri. 2019. "A Global Databased of Power Plants." Washington DC. http://globalenergyobservatory.org.

Carattini, Stefano, Steffen Kallbekken, and Anton Orlov. 2019. "How to Win Public Support for a Global Carbon Tax." Nature 565 (7739): 289–91. https://www.nature.com/articles/d41586-019-00124-x.

Caron, Justin, and Thibault Fally. 2022. "Per Capita Income, Consumption Patterns, and CO2 Emissions." Journal of the Association of Environmental and Resource Economists 9 (2): 235–71. https://doi.org/10.1086/716727.

Center for International Earth Science Information Network (CIESIN) Columbia University. 2018a. "Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets." Palisades NY. https://doi.org/10.7927/H45Q4T5F.

Cerra, Valerie, Zamid Aligishiev, Vybhavi Balasundharam, Simon Black, Chen Chen, Majdeline El Rayess, Dominique Fayad, et al. 2022. "Republic of Madagascar: Technical Assistance Report-Climate Macroeconomic Assessment Program." https://www.imf.org/en/Publications/CR/Issues/2022/11/14/Republic-of-Madagascar-Technical-Assistance-Report-Climate-Macroeconomic-Assessment-Program-525665.

Chateau, Jean, Gregor Schwerhoff, and Florence Jaumotte. 2022. "Economic and Environmental Benefits from International Cooperation on Climate Policies." Departmental Paper No 2022/007. https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2022/03/16/Economic-and-Environmental-Benefits-from-International-Cooperation-on-Climate-Policies-511562.

Chattopadhyay, D., De Sisternes, F., Oguah, S. K. W., "World Bank Electricity Planning Model (EPM) Mathematical Formulation", 2018, Energy Sector Management Assistance Program (ESMAP), International Bank for Reconstruction and Development, The World Bank, Washington DC. https://github.com/worldbank/EPM.

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. https://doi.org/10/ghszxg.

Coady, David, Margaret E. Grosh, and John Hoddinott. 2004. "Targeting of Transfers in Developing Countries: Review of Lessons and Experience."

Cohen, Mark A., and Adeline Tubb. 2018. "The Impact of Environmental Regulation on Firm and Country Competitiveness: A Meta-Analysis of the Porter Hypothesis." *Journal of the Association of Environmental and Resource Economists* 5 (2). https://doi.org/10.1086/695613.

Cramton, Peter, and Suzi Kerr. 2002. "Tradeable carbon permit auctions: How and why to auction not grandfather." *Energy policy* 30 (4): 333-345.

Crippa, M., D. Guizzardi, M. Muntean, E. Schaaf, E. Solazzo, F. Monforti-Ferrario, J. Olivier, and E. Vignati. 2020. "Fossil CO2 and GHG Emissions of all World Countries: 2020 Report." Joint Research Centre, European Commission, Brussels.

Dimitropoulos, Alexandros, Walid Oueslati, and Christina Sintek. 2018. "The Rebound Effect in Road Transport: A Meta-Analysis of Empirical Studies." Energy Economics 75: 163–79. https://doi.org/10.1016/j.eneco.2018.07.021.

Dingenen, Rita Van, Frank Dentener, Monica Crippa, Joana Leitao, Elina Marmer, Shilpa Rao, Efisio Solazzo, and Luana Valentini. 2018. "TM5-FASST: A Global Atmospheric Source–Receptor Model for Rapid Impact Analysis of Emission Changes on Air Quality and Short-Lived Climate Pollutants."

Atmospheric Chemistry and Physics 18 (21): 16173–211. https://doi.org/10.5194/acp-18-16173-2018.

Dolphin, Geoffroy, Michael G Pollitt, and David M Newbery. 2020. "The Political Economy of Carbon Pricing: A Panel Analysis." Oxford Economic Papers 72 (2): 472–500. https://doi.org/10.1093/oep/gpz042.

Dolphin, Geoffroy G., and Michael G. Pollitt. 2021. "The International Diffusion of Climate Policy: Theory and Evidence." https://www.rff.org/publications/working-papers/the-international-diffusion-of-climate-policy-theory-and-evidence/.

Enerdata. 2022. "Global Energy & CO2 Data." https://www.enerdata.net/research/energy-market-data-co2-emissions-database.html.

Energy Information Administration (EIA), 2014. Annual Energy Outlook 2016. Energy Information Administration, US Department of Energy, Washington, DC.

Eskander, Shaikh M. S. U., and Sam Fankhauser. 2023. "The Impact of Climate Legislation on Trade-Related Carbon Emissions 1996–2018." Environmental and Resource Economics. https://doi.org/10.1007/s10640-023-00762-w.

Fabrizio, Stefania, Alexei Goumilevski, and Kangni Kpodar. 2016. "A New Tool for Distributional Incidence Analysis: An Application to Fuel Subsidy Reform." Vol. 16. https://doi.org/10.5089/9781475546743.005.

Food and Agriculture Organization (FAO). 2018. "Emissions Due to Agriculture," https://www.fao.org/3/cb3808en/cb3808en.pdf.

Food and Agriculture Organization Corporate Statistical Database (FAOSTAT). 2022. Statistical Database. Rome.

Forsell, Nicklas, Olga Turkovska, Mykola Gusti, Michael Obersteiner, Michel den Elzen, and Petr Havlik. 2016. "Assessing the INDCs' Land Use, Land Use Change, and Forest Emission Projections." Carbon Balance and Management 11 (1): 26. https://doi.org/10.1186/s13021-016-0068-3.

Fried, Stephie., 2018. "Climate Policy and Innovation: A Quantitative Macroeconomic Analysis." *American Economic Journal: Macroeconomics* 10: 90-118

Friedlingstein, Pierre, Matthew W. Jones, Michael O'Sullivan, Robbie M. Andrew, Dorothee C. E. Bakker, Judith Hauck, Corinne Le Quéré, and others 2021. "Global Carbon Budget 2021." Earth System Science Data Discussions, November, 1–191. https://doi.org/10.5194/essd-2021-386.

Ganapati, Sharat, Joseph S. Shapiro, and Reed Walker. 2020. "Energy Cost Pass-Through in US Manufacturing: Estimates and Implications for Carbon Taxes." American Economic Journal: Applied Economics 12 (2): 303–42. https://doi.org/10.1257/app.20180474.

Gertler, Paul J., Orie Shelef, Catherine D. Wolfram, and Alan Fuchs. 2016. "The Demand for Energy-Using Assets among the World's Rising Middle Classes." American Economic Review 106 (6): 1366–1401. https://doi.org/10.1257/aer.20131455.

Kenneth Gillingham and James H. Stock, "The Cost of Reducing Greenhouse Gas Emissions," Journal of Economic Perspectives 32, no. 4 (2018): 53–72, https://doi.org/10.1257/jep.32.4.53.

Global Burden of Disease (GBD). 2020. "Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990-2019: A Systematic Analysis for the Global Burden of Disease Study 2019." The Lancet. Vol. 396. Elsevier. https://doi.org/10.1016/S0140-6736(20)30752-2.

Global Burden of Disease (GBD). 2019. "Global Expected Health Spending 2017-2050." Seattle, United States: Institute for Health Metrics and Evaluation. http://ghdx.healthdata.org/record/ihme-data/global-expected-health-spending-2017-2050.

Global Fuel Economy Initiative and IEA. 2021. “Vehicle Fuel Economy in Major Markets 2005-2019.” Global Fuel Economy Initiative. https://www.globalfueleconomy.org/media/792005/wp22-vehicle-fuel-economy-in-major-markets.pdf.

Grassi, Giacomo, Jo House, Werner A. Kurz, Alessandro Cescatti, Richard A. Houghton, Glen P. Peters, Maria J. Sanz, and others 2018. “Reconciling Global-Model Estimates and Country Reporting of Anthropogenic Forest CO2 Sinks.” Nature Climate Change 8 (10): 914–20. https://doi.org/10.1038/s41558-018-0283-x.

Grubb, Michael, Paul Drummond, Jean-Francois Mercure, Cameron Hepburn, Peter Barbrook-Johnson, João Carlos Ferraz, Alex Clark, et al. 2021. “The New Economics of Innovation and Transition: Evaluating Opportunities and Risks”. https://www.oxfordmartin.ox.ac.uk/publications/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/.

Hallegatte, Stéphane, Marianne Fay, and Adrien Vogt-Schilb. 2013. “Green Industrial Policies - When and How.” World Bank Policy Research Working Papers, no. October: 26. https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-6677.

Harring, Niklas, Erik Jönsson, Simon Matti, Gabriela Mundaca, and Sverker C. Jagers. 2023. “Public Acceptance of Fossil Fuel Subsidy Removal Can Be Reinforced with Revenue Recycling.” Nature Climate Change, February, 1–2. https://doi.org/10.1038/s41558-023-01609-4.

Harberger, Arnold C., 1964. “The Measurement of Waste.” *American Economic Review* 54: 8-76.

Harmsen, M. J. H. M., D. P. van Vuuren, D. R. Nayak, A. F. Hof, L. Höglund-Isaksson, P. L. Lucas, J. B. Nielsen, P. Smith, and E. Stehfest. 2019. “Long-Term Marginal Abatement Cost Curves of Non-CO2 Greenhouse Gases.” Environmental Science and Policy 99: 136–49.

Heine, Dirk, and Simon J. Black. 2019. “Benefits Beyond Climate: Environmental Tax Reform in Developing Countries.” In Fiscal Policies for Development and Climate Action, edited by Miria A. Pigato, 1–56. Washington DC. https://elibrary.worldbank.org/doi/10.1596/978-1-4648-1358-0_ch1.

Hoesly, Rachel M., Steven J. Smith, Leyang Feng, Zbigniew Klimont, Greet Janssens-Maenhout, Tyler Pitkanen, Jonathan J. Seibert, and others. 2018. “Historical (1750–2014) Anthropogenic Emissions of Reactive Gases and Aerosols from the Community Emissions Data System (CEDS).” Geoscientific Model Development 11: 369–408.

Holland, Mike. 2014. “CBA for the Clean Air Policy Package Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package Version 2 Corresponding to IIASA TSAP Report No. 11, Version 2.”

Kristy Howell, Simon Black, Rainer Lanz, Marc Bacchetta, and Enxhi Tresa. 2023. “Trade in Low-Carbon Technology Products.” In Data for a Greener World: A Guide for Practitioners and Policymakers. International Monetary Fund. https://www.elibrary.imf.org/display/book/9798400217296/9798400217296.xml.

Humbert, Sebastien, Julian Marshall, Shanna Shaked, Joseph Spadaro, Yurika Nishioka, Philipp Preiss, Thomas McKone, Arpad Horvath, and Olivier Jolliet. 2011. “Intake Fraction for Particulate Matter: Recommendations for Life Cycle Impact Assessment.” Environmental Science & Technology TA - TT - 45 (11): 4808. https://pubmed.ncbi.nlm.nih.gov/21563817/.

Institute for Health Metrics and Evaluation (IHME), 2020. Global Burden of Disease: Results Tool. Institute for Health Metrics and Evaluation, University of Washington, 2020. http://ghdx.healthdata.org/gbd-results-tool.

Institute for Health Metrics and Evaluation (IHME), 2021. “GBD Results Tool.” http://ghdx.healthdata.org/gbd-results-tool.

International Institute for Applied Systems Analysis (IIASA), 2021. “SSP Database (Shared Socioeconomic Pathways) - Version 2.0,”, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10.

International Energy Agency (IEA). 2021. “World Energy Outlook 2021.” https://www.iea.org/reports/world-energy-outlook-2021.

International Energy Agency (IEA). 2022a. “World Energy Outlook 2022.” https://www.iea.org/reports/world-energy-outlook-2022.

———. 2022b. “Energy Efficiency 2022.” Energy Efficiency. https://www.iea.org/reports/energy-efficiency-2022.

———. 2022c. “Global Methane Tracker 2022.” https://www.iea.org/reports/global-methane-tracker-2022.

International Monetary Fund (IMF). 2019a. Fiscal Monitor October 2019: How to Mitigate Climate Change. Washington, DC. https://www.imf.org/en/Publications/FM/Issues/2019/10/16/Fiscal-Monitor-October-2019-How-to-Mitigate-Climate-Change-47027.

———. 2019b. “Fiscal Policies for Paris Climate Strategies – From Principle to Practice.” Washington DC: IMF. https://www.imf.org/~/media/Files/Publications/PP/2019/PPEA2019010.ashx.

———. 2021a. “Canada: Selected Issues.” Country Report No. 2021/055. https://www.imf.org/en/Publications/CR/Issues/2021/03/17/Canada-Selected-Issues-50274.

———. 2021b. “Regional Economic Outlook for Latin America and the Caribbean, October 2021.” https://www.imf.org/en/Publications/REO/WH/Issues/2021/10/21/Regional-Economic-Outlook-October-2021-Western-Hemisphere.

———. 2021c. “Republic of Korea: Selected Issues.” Country Report No. 2021/065. https://www.imf.org/en/Publications/CR/Issues/2021/03/24/Republic-of-Korea-Selected-Issues-50307.

———. 2022a. “Fiscal Monitor April 2022: Chapter 2: Coordinating Taxation Across Borders”. Washington, DC. https://www.imf.org/-/media/Files/Publications/fiscal-monitor/2022/April/English/ch2.ashx.

———. 2022b. “Greece: Selected Issues.” Country Report No. 2022/174. https://www.imf.org/en/Publications/CR/Issues/2022/06/16/Greece-Selected-Issues-519674.

———.2022c. “Philippines: Selected Issues.” Country Report No. 2022/370. https://www.imf.org/en/Publications/CR/Issues/2022/12/15/Philippines-Selected-Issues-526988.

———. 2022d. “South Africa: Selected Issues.” Country Report No. 2022/038. https://www.imf.org/en/Publications/CR/Issues/2022/02/10/South-Africa-Selected-Issues-513004

———. 2022e. “Thailand: Selected Issues.” Country Report No. 2022/301. https://www.imf.org/en/Publications/CR/Issues/2022/09/16/Thailand-Selected-Issues-523535.

———. 2022f. “Vietnam: 2022 Article IV Consultation-Press Release; Staff Report, and Statement by the Executive Director for Vietnam.” IMF Country Report No. 22/209. https://www.imf.org/en/Publications/CR/Issues/2022/07/05/Vietnam-2022-Article-IV-Consultation-Press-Release-Staff-Report-and-Statement-by-the-520395.

———. 2022g. “World Economic Outlook, October 2022: Countering the Cost-of-Living Crisis.” Washington DC. https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022.

———. 2022h. “Staff Guidance Note on the Sovereign Risk and Debt Sustainability Framework for Market Access Countries.” Policy Papers 2022 (039): 1. https://doi.org/10.5089/9798400216862.007.

———. 2023a. “Chile: Technical Assistance Report - An Evaluation of Improved Tax Options.” IMF. 2023. https://www.imf.org/en/Publications/CR/Issues/2023/01/19/Chile-Technical-Assistance-Report-An-Evaluation-of-Improved-Tax-Options-528348.

———.2023b. “Peru: 2023 Article IV Consultation-Press Release; Staff Report; and Statement by the Executive Director for Peru.” IMF IMF, 2023.

https://www.imf.org/en/Publications/CR/Issues/2023/03/24/Peru-2023-Article-IV-Consultation-Press-Release-Staff-Report-and-Statement-by-the-Executive-531362.

Intergovernmental Panel on Climate Change (IPCC), J. Penman, Michael Gytarsky, T. Hiraishi, W. Irving, and T. Krug. 2006. “2006 Guidelines for National Greenhouse Gas Inventories.” https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

———. 2019. “Refinement To the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.” Fundamental and Applied Climatology 2: 5–13. https://doi.org/10.21513/0207-2564-2019-2-05-13.

———. 2021. “Sixth Assessment Report (AR6): Contribution from Working Group I.” Climate Change 2021: The Physical Science Basis, August. https://www.ipcc.ch/report/ar6/wg1/.

———. 2022. “Climate Change 2022: Mitigation of Climate Change.” Intergovernmental Panel on Climate Change Working Group III, Contribution to the Sixth Assessment Report. https://www.ipcc.ch/report/ar6/wg3/.

International Road Federation (IRF). 12021. World Road Statistics. International Road Federation.

Keith, David R., Samantha Houston, and Sergey Naumov. 2019. "Vehicle fleet turnover and the future of fuel economy." Environmental Research Letters 14 (2): 021001.

Kholod, Nazar, Meredydd Evans, Raymond C. Pilcher, Volha Roshchanka, Felicia Ruiz, Michael Coté, Ron Collings. 2020. “Global methane emissions from coal mining to continue growing even with declining coal production.” Journal of Cleaner Production, Volume 256, 2020, https://doi.org/10.1016/j.jclepro.2020.120489.

Knobloch, Florian, Hector Pollitt, Unnada Chewpreecha, Vassilis Daioglou, and Jean-Francois Mercure. 2019. “Simulating the Deep Decarbonisation of Residential Heating for Limiting Global Warming to 1.5 °C.” Energy Efficiency 12 (2): 521–50. https://doi.org/10.1007/s12053-018-9710-0.

Kpodar, Kangni, and Chadi Abdallah. 2016. Dynamic Fuel Price Pass-Through: Evidence from a New Global Retail Fuel Price Database. Washington DC: IMF. https://www.imf.org/en/Publications/WP/Issues/2016/12/31/Dynamic-Fuel-Price-Pass-Through-Evidence-from-a-New-Global-Retail-Fuel-Price-Database-44499.

Krupnick, Alan J., Ian WH Parry, Margaret Walls, Tony Knowles, and Kristin Hayes. 2010. “Toward a New National Energy Policy: Assessing the Options.” Resources for the Future, Washington, DC. https://www.ourenergypolicy.org/wp-content/uploads/2013/06/RFF-NEPI-Full-Report-Final-Nov-2010.pdf.

Lauvaux, T., C. Giron, M. Mazzolini, A. D’Asprement, R. Duren, D. Cusworth, D. Shindell, and P Ciai. 2022. “Global Assessment of Oil and Gas Methane Ultra-Emitters.” Science 375: 557–61.

Labandeira, Xavier, José Labeaga, and Xiral López-Otero. 2017. “A Meta-Analysis on the Price Elasticity of Energy Demand.” Energy Policy 102: 549–68. https://doi.org/10.1016/j.enpol.2017.01.002.

Leontief, W. 1986. Input-Output Economics. 2nd Edition, Oxford University Press, New York.

Li, Shanjun, Joshua Linn, and Erich Muehlegger. 2014. “Gasoline Taxes and Consumer Behavior.” American Economic Journal: Economic Policy 6 (4): 302–42. https://doi.org/10.1257/pol.6.4.302.

Linsenmeier, Manuel, Adil Mohommad, and Gregor Schwerhoff. 2022a. “Policy Sequencing Towards Carbon Pricing - Empirical Evidence from G20 Economies and Other Major Emitters.” IMF Working Papers, no. 2022/066. https://www.imf.org/en/Publications/WP/Issues/2022/04/01/Policy-Sequencing-Towards-Carbon-Pricing-Empirical-Evidence-From-G20-Economies-and-Other-515609.

———. 2022b “The International Diffusion of Policies for Climate Change Mitigation.” IMF Working Papers 2022, no. 115 (June 2022): 1. https://doi.org/10.5089/9798400213090.001.

Liddle, Brantley, and Hillard Huntington. 2020. "Revisiting the Income Elasticity of Energy Consumption: A Heterogeneous, Common Factor, Dynamic OECD & Non-OECD Country Panel Analysis." The Energy Journal 41 (3). https://doi.org/10.5547/01956574.41.3.blid.

Luca, Oana, and Diego Mesa Puyo. 2016. "Fiscal Analysis of Resource Industries: (FARI Methodology)." Technical Notes and Manuals 2016 (01): 1. https://doi.org/10.5089/9781513575117.005.

Mas-Colell, Andreu, Michael Dennis Whinston, and Jerry R. Green. 1995. Microeconomic Theory. New York: Oxford University Press.

Mercer-Blackman, Valerie, Lazar Milivojevic, Victor Mylonas, and Yi Li. (2022). Charting the Course to a New Normal. In South Asia Economic Focus: Reshaping Norms: A New Way Forward. World Bank Group.

Mercure, Jean-François. 2012. "FTT:Power : A Global Model of the Power Sector with Induced Technological Change and Natural Resource Depletion." Energy Policy, Special Section: Frontiers of Sustainability, 48 (September): 799–811. https://doi.org/10.1016/j.enpol.2012.06.025.

Mercure, Jean-François., A. Lam, S. Billington, and H. Pollitt. 2018. "Integrated Assessment Modelling as a Positive Science: Private Passenger Road Transport Policies to Meet a Climate Target Well below 2 ∘C." Climatic Change 151 (2): 109–29. https://doi.org/10.1007/s10584-018-2262-7.

Metcalf, Gilbert E., and James H. Stock. 2020. "Measuring the Macroeconomic Impact of Carbon Taxes." AEA Papers and Proceedings 110 (May): 101–6. https://doi.org/10.1257/pandp.20201081.

Minx, J. C., T. Wiedmann, R. Wood, G. P. Peters, M. Lenzen, A. Owen, K. Scott, and others 2009. Input-Output Analysis and Carbon Footprinting: An Overview of Applications. Economic Systems Research. Vol. 21. https://doi.org/10.1080/09535310903541298.

Moore, Nils aus dem, Johannes Brehm, and Henri Gruhl. 2021. "Driving Innovation? Carbon Tax Effects in the Swedish Transport Sector." SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3995632.

National Research Council (NRC), 2010, "Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use". National Research Council, National Academies. https://nap.nationalacademies.org/read/12794/chapter/2

Neuhoff, Karsten, and Robert A. Ritz. 2019. "Carbon Cost Pass-Through in Industrial Sectors." Vol. 45. https://ideas.repec.org/p/cam/camdae/1988.html.

Organization for Economic Cooperation and Development (OECD), 2012. Mortality Risk Valuation in Environment, Health and Transport Policies, Mortality Risk Valuation in Environment, https://doi.org/10.1787/9789264130807-en.

———. 2020. "Health Status: Absence from Work Due to Illness." 2020. https://stats.oecd.org/index.aspx?queryid=30123.

Ostro, Bart. 1987. "Air Pollution and Morbidity Revisited: A Specification Test." Journal of Environmental Economics and Management 14 (1): 87–98. https://doi.org/10.1016/0095-0696(87)90008-8.

Parry, Ian, Roberton Williams, and Lawrence Goulder. 1999. "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets." Journal of Environmental Economics and Management 37: 52–84. https://www.sciencedirect.com/science/article/pii/S0095069698910580.

Parry, Ian, John Norregaard, and Dirk Heine, 2012. "Environmental Tax Reform: Principles from Theory and Practice to Date." Annual Review of Resource Economics 4: 101–125. https://www.annualreviews.org/doi/abs/10.1146/annurev-resource-110811-114509.

Parry, Ian, Dirk Heine, Eliza Lis, and Shanjun Li. 2014. "Getting Energy Prices Right: From Principle to Practice". Washington DC: IMF. http://elibrary.imf.org/view/IMF071/21171-9781484388570/21171-9781484388570/21171-9781484388570.xml.

Parry, Ian, Chandara Veung and Dirk Heine, 2015. "How Much Carbon Pricing is in Countries Own Interests? The Critical Role of Co-Benefits." *Climate Change Economics* 6, 1550019-1-26. https://www.jstor.org/stable/climchanecon.6.4.05.

Parry, Ian, and Victor Mylonas. 2017. Canada's Carbon Price Floor. National Tax Journal, 70(4), 879-900.

Parry, Ian, Victor Mylonas, and Nate Vernon. 2019. Reforming Energy Policy in India: Assessing the Options. In Handbook on Green Growth. Edward Elgar Publishing.

Parry, Ian, Baoping Shang, Nate Vernon, and Philippe Wingender, 2020. "Evaluating Policies to Implement the Paris Agreement: A Toolkit with Application to China." In G. Chichilnisky and A. Rezai (eds.) Handbook on the Economics of Climate Change, Edward Elgar, Northampton, MA, 32-67.

Parry, Ian, Simon Black, and James Roaf. 2021a. "Proposal for an International Carbon Price Floor among Large Emitters," IMF Staff Climate Notes, no. 2021/001. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2021/06/15/Proposal-for-an-International-Carbon-Price-Floor-Among-Large-Emitters-460468.

Parry, Ian, Victor Mylonas, and Nate Vernon. 2021b. "Mitigation Policies for the Paris Agreement: An Assessment for G20 Countries." Journal of the Association of Environmental and Resource Economics 8. https://www.journals.uchicago.edu/doi/10.1086/713147.

Parry, Ian, Simon Black, and Nate Vernon. 2021c. "Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies." IMF Working Papers, Working Paper No. 2021/236. https://www.imf.org/en/Publications/WP/Issues/2021/09/23/Still-Not-Getting-Energy-Prices-Right-A-Global-and-Country-Update-of-Fossil-Fuel-Subsidies-466004.

Parry, Ian, Christophe Waerzeggers, Cory Hillier, James Roaf, Florian Misch, Martin Kaufman, and Kyung Kwak. 2021d. "Carbon Pricing: What Role for Border Carbon Adjustments?", IMF Staff Climate Note 2021/004, International Monetary Fund, Washington, DC., . https://www.imf.org/en/Publications/staff-climate-notes/Issues/2021/09/24/Carbon-Pricing-What-Role-for-Border-Carbon-Adjustments-464805.

Parry, Ian, Simon Black, and Karlygash Zhunussova. 2022a. "Carbon Taxes or Emissions Trading Systems? Instrument Choice and Design," IMF Staff Climate Notes, No 2022/006. https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/07/14/Carbon-Taxes-or-Emissions-Trading-Systems-Instrument-Choice-and-Design-519101.

Parry, Ian, Simon Black, Danielle Minnett, Victor Mylonas, and Nate Vernon. 2022b. "How to Cut Methane Emissions." IMF Staff Climate Notes 2022 (008). https://doi.org/10.5089/9798400224256.066.

Parry, Ian, Danielle Minnett, and Karlygash Zhunussova. 2023a. "Climate Mitigation Policy in Türkiye." IMF Working Paper.

Parry, Ian, Simon Black, and Nate Vernon. 2023b. "Measuring Fossil Fuel Subsidies—A Global and Country View." In Data for a Greener World: A Guide for Practitioners and Policymakers, 95-112 International Monetary Fund. https://www.elibrary.imf.org/display/book/9798400217296/9798400217296.xml.

Perino, Grischa, and Till Requate. 2012. "Does More Stringent Environmental Regulation Induce or Reduce Technology Adoption? When the Rate of Technology Adoption Is Inverted U-Shaped." *Journal of Environmental Economics and Management*, 2010 Monte Verita Conference on Sustainable Resource Use and Economic Dynamics (SURED), 64, no. 3: 456–67. https://doi.org/10.1016/j.jeem.2012.03.001.

Peñasco, Cristina, Laura Díaz Anadón, and Elena Verdolini. 2021. "Systematic Review of the Outcomes and Trade-Offs of Ten Types of Decarbonization Policy Instruments." Nature Climate Change 11 (3): 257–65. https://doi.org/10.1038/s41558-020-00971-x.

Pigato, Miria A, Simon Black, Damien Dussaux, Zhimin Mao, Miles Mckenna, Ryan Rafaty, and Simon Touboul. 2020a. Technology Transfer and Innovation for Low-Carbon Development. https://openknowledge.worldbank.org/handle/10986/33474.

Pigato, Miria A, Simon Black, Damien Dussaux, Zhimin Mao, Miles McKenna, Ryan Rafaty, and Simon Touboul. 2020b. “Policies to Support Low-Carbon Technology Transfer.” In Technology Transfer and Innovation for Low-Carbon Development, 109–52. https://doi.org/10.1596/978-1-4648-1500-3_ch5.

Preker, Alexander, Olusoji Adeyi, Marisa Lapetra, Diane Simon, and Eric Keuffel. 2016. “Health Care Expenditures Associated with Pollution: Exploratory Methods and Findings.” Annals of Global Health 82 (5): 711–21. https://doi.org/10.1016/j.aogh.2016.12.003.

Prest, Brian, Dallas Burtraw, and Karen Palmer. 2021. “Waiting for Clarity: How a Price on Carbon Can Inspire Investment,” https://media.rff.org/documents/Rpt_21-08_final.pdf.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, et al. 2022. “Comprehensive Evidence Implies a Higher Social Cost of CO2.” *Nature* 610, no. 7933: 687–92. https://doi.org/10.1038/s41586-022-05224-9.

Robinson, Lisa., James Hammitt, and Lucy O’Keeffe. 2019. “Valuing Mortality Risk Reductions in Global Benefit-Cost Analysis.” Journal of Benefit-Cost Analysis, 10(S1), 15-50. https://doi.org/10.1017/bca.2018.26

Ruhnau, O., M. Bucksteeg, D. Ritter, R. Schmitz, D. Böttger, M. Koch, A. Pöstges, M. Wiedmann, and L. Hirth. 2022. “Why Electricity Market Models Yield Different Results: Carbon Pricing in a Model-Comparison Experiment.” Renewable and Sustainable Energy Reviews 153 (January): 111701. https://doi.org/10.1016/j.rser.2021.111701.

Saunders, Harry D., Joyashree Roy, Inês M.L. Azevedo, Debalina Chakravarty, Shyamasree Dasgupta, Stephane de la Rue du Can, Angela Druckman, and others 2021. “Energy Efficiency: What Has Research Delivered in the Last 40 Years?” Annual Review of Environment and Resources 46 (1): 135–65. https://doi.org/10.1146/annurev-environ-012320-084937.

Schoder, Christian. 2022. “Regime-Dependent Environmental Tax Multipliers: Evidence from 75 Countries.” Journal of Environmental Economics and Policy 0 (0): 1–44. https://doi.org/10.1080/21606544.2022.2089238.

Schwingshackl, Clemens, Wolfgang A. Obermeier, Selma Bultan, Giacomo Grassi, Josep G. Canadell, Pierre Friedlingstein, Thomas Gasser, et al. 2022. “Differences in Land-Based Mitigation Estimates Reconciled by Separating Natural and Land-Use CO2 Fluxes at the Country Level.” One Earth 5 (12): 1367–76. https://doi.org/10.1016/j.oneear.2022.11.009.

Shang, B., 2023. The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications. *Review of Environmental Economics and Policy*, 17(1).

Socioeconomic Data and Applications Center (SEDAC). 2018. “Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11.” Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4JW8BX5.

Stuermer, Lukas, Andrea Boer, and Martin Pescatori. 2021. “Energy Transition Metals.” IMF Working Papers, no. WP/21/243. https://www.imf.org/en/Publications/WP/Issues/2021/10/12/Energy-Transition-Metals-465899.

Tubiello, Francesco N., Giulia Conchedda, Nathan Wanner, Sandro Federici, Simone Rossi, and Giacomo Grassi. 2021. “Carbon Emissions and Removals from Forests: New Estimates, 1990–2020.” Earth System Science Data 13 (4): 1681–91. https://doi.org/10.5194/essd-13-1681-2021.

Turner, Michelle, Michael Jerrett, Arden Pope, Daniel Krewski, Susan Gapstur, Ryan Diver, Bernardo Beckerman, and others 2016. “Long-Term Ozone Exposure and Mortality in a Large Prospective Study.” American Journal of Respiratory and Critical Care Medicine 193 (10): 1134–42. https://doi.org/10.1164/rccm.201508-1633OC.

Truby, Johannes, and Moritz Paulus. 2012. “Market Structure Scenarios in International Steam Coal Trade.” *The Energy Journal* 33, no. 3. https://doi.org/10.5547/01956574.33.3.4.

United Nations Statistics Division. 2020. "Energy Statistics." https://unstats.un.org/unsd/energystats/pubs/balance/

United States Environment Protection Agency (EPA). 2019. "Global Non-CO2 Greenhouse Gas Emission Projections and Mitigation Potential: 2015–2050." Washington, DC.

Vercoulen, Pim, and Sanna Markkanen. 2019. "Technology, Employment, and Climate Change Mitigation: Modelling the Iron and Steel Industry." Cambridge, UK: CLG Europe. https://www.corporateleadersgroup.com/system/files/documents/steel-modelling-paper.pdf.

Vernon, Nate. 2023. "Fiscal Policy Options to Accelerate Emissions Reductions in Belgium." IMF Selected Issues Paper No. 2023/017. https://www.imf.org/en/Publications/selected-issues-papers/Issues/2023/03/03/Fiscal-Policy-Options-to-Accelerate-Emissions-Reductions-in-Belgium-Belgium-Belgium-530525.

Viscusi, Kip., and Clayton Masterman. 2017. "Income Elasticities and Global Values of a Statistical Life." Journal of Benefit-Cost Analysis, 8(2), 226-250. https://doi.org/10.1017/bca.2017.12

Vogt-Schilb, Adrien, Guy Meunier, and Stéphane Hallegatte. 2018. "When Starting with the Most Expensive Option Makes Sense: Optimal Timing, Cost and Sectoral Allocation of Abatement Investment." Journal of Environmental Economics and Management 88: 210–33. https://doi.org/10.1016/j.jeem.2017.12.001.

Wagner, Fabian, J Borken-Kleefeld, G Kiesewetter, Z Klimont, W Schoepp, and Marcus Amann. 2020. "Implied Emission Factors in the World Bank's Climate Policy Assessment Tool (CPAT)." 2020. http://dare.iiasa.ac.at/87/.

Webster, Mort, Sergey Paltsev, and John Reilly. "Autonomous Efficiency Improvement or Income Elasticity of Energy Demand: Does It Matter?" *Energy Economics, Technological Change and the Environment*, 30, no. 6 (November 1, 2008): 2785–98. https://doi.org/10.1016/j.eneco.2008.04.004.

Wingender, Philippe, and Florian Misch. 2021. "Revisiting Carbon Leakage." IMF Working Papers 2021 (207): 1. https://doi.org/10.5089/9781513593029.001.

Wingender, Philippe, and Ian W. H. Parry. 2021. "Fiscal Policies for Achieving Finland's Emission Neutrality Target." *IMF Working Paper No. 2021/171*. https://www.imf.org/en/Publications/WP/Issues/2021/06/25/Fiscal-Policies-for-Achieving-Finlands-Emission-Neutrality-Target-460890.

Way, Rupert, Matthew C Ives, Penny Mealy, and J Doyne Farmer. 2021. "Empirically Grounded Technology Forecasts and the Energy Transition" https://www.inet.ox.ac.uk/files/energy_transition_paper-INET-working-paper.pdf.

Werner Kevin. 2021. "What is the lifespan of a commercial building?" Available at http://www.shingobee.com/About-Us/News/entryid/191/what-is-the-lifespan-of-a-commercial-building-ask-the-expert#:~:text=The%20lifespan%20of%20a%20commercial%20building%20on%20average%20ranges%20from,build%20quality%20and%20maintenance%20management.

World Bank. 2022a. "Carbon Pricing Dashboard." https://carbonpricingdashboard.worldbank.org/.

_____. 2022b. "What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050." https://datatopics.worldbank.org/what-a-waste/

World Health Organization (WHO). 2015. "Database on Source Apportionment Studies for Particulate Matter in the Air" 2015. https://www.who.int/data/gho/data/themes/air-pollution/source-apportionment-db.

_____. 2019. "Absenteeism from Work Due to Illness, Days per Employee per Year." 2019.

Zhu, Xing, Lanlan Li, Kaile Zhou, Xiaoling Zhang, and Shanlin Yang. 2018. "A Meta-Analysis on the Price Elasticity and Income Elasticity of Residential Electricity Demand." Journal of Cleaner Production 201 (November): 169–77. https://doi.org/10.1016/j.jclepro.2018.08.027

PUBLICATIONS

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