// NO.25-021 | 06/2025

DISCUSSION PAPER

// TIM KALMEY, SEBASTIAN RAUSCH, AND JAN SCHNEIDER

The Welfare Effects of Explicit and Implicit Subsidies on Fossil Fuels

Leibniz Association

ZEW

The Welfare Effects of Explicit and Implicit Subsidies on Fossil Fuels

By Tim Kalmey, Sebastian Rausch, and Jan Schneider*

June 2025

We examine the welfare effects of removing explicit and implicit fossil fuel subsidies, the latter entailing Pigouvian pricing of local externalities from fossil energy consumption. We map a multi-region, multi-sector general equilibrium model to granular data on subsidies, local marginal external costs, and national income and product accounts. On average, unilateral Pigouvian pricing improves a country's welfare by 3.7%, generates fiscal revenues equal to 2.5% of consumption, and reduces the carbon price needed to meet the Paris climate target by 76%. Non-market welfare gains exceed market-related losses, benefiting most countries. Local air pollution pricing accounts for 90% of net benefits. About one third of countries would already meet their climate targets, making additional policies like carbon pricing redundant. For all countries, combining Pigouvian energy pricing with carbon pricing increases welfare compared to relying on carbon pricing alone. Removing explicit subsidies has a minor impact on welfare and emissions. Global Pigouvian energy pricing would reduce global emissions by 32%, while increasing global welfare by 2.4%. Our findings underscore the potential of Pigouvian energy pricing to align economic, fiscal, and climate goals.

Keywords: *Fossil Fuels, Subsidies, Externalities, Pigouvian Taxation, Climate Policy, Co-Benefits, General Equilibrium*
JEL Classification: *C68, H23, Q43, Q58*

The fundamental problem posed by climate change is that it is a global public good: while the mitigation costs of reducing greenhouse gas (GHG) emissions are local, the benefits are global (or individual nations enjoy only a small fraction of the benefits of their actions). Strong free-rider incentives for individual countries hamper cooperative multinational policies to internalize climate damages caused

* Kalmey (tim.kalmey@zew.de), ZEW Leibniz Centre for European Economic Research, Mannheim, Germany. Rausch (sebastian.rausch@zew.de), ZEW Leibniz Centre for European Economic Research, Mannheim, Germany, Department of Economics, Heidelberg University, Germany, Centre for Energy Policy and Economics at ETH Zurich, Switzerland, and Joint Program on the Science and Policy of Global Change at Massachusetts Institute of Technology, Cambridge, USA. Schneider (jan.schneider@uol.de): Department of Business Administration, Economics and Law, Carl von Ossietzky University Oldenburg, Germany. We thank Maksym Chepeliev and GTAP for providing us with updated estimates on fossil fuel subsidies. The authors gratefully acknowledge funding by the European Commission under the Horizon Europe project "Welfare systems and labour market policies for economic and social resilience in Europe".

by the use of fossil energy sources (Barrett, 1994; Barrett and Stavins, 2003; Nordhaus, 2019). Indeed, theory suggests that for a collective action problem such as global climate change, free riding becomes more problematic the greater are the aggregate gains to cooperation (Barrett, 2003), which is particularly the case if climate damages increase. Overcoming the free-rider problem thus requires a restructuring of the underlying incentives.

This paper examines the incentives for reducing fossil energy consumption at the local (i.e. country or regional) level when the global climate externality is ignored. Global economies heavily rely on fossil fuels, incurring significant costs from local externalities that are not internalized in market decisions. A series of influential IMF reports (Coady et al., 2019; Parry, Black and Vernon, 2021; Black et al., 2023) show that many countries continue to heavily subsidize fossil fuels, both explicitly (by undercharging supply costs) and implicitly (by failing to account for the non-market costs associated with local externalities of fossil fuel use). Global fossil fuel subsidies in 2022 totaled \$7 trillion (7.1% of global GDP) in 2022, of which 18% account for explicit and 82% for implicit subsidies.[1,2] On a policy level, reform efforts to phase out inefficient fossil fuel subsidies have been ongoing since the G20's 2019 and 2020 commitments, reaffirmed at the United Nations Climate Change Conferences in 2021 and 2022.

We analyze three main questions: What incentives do countries and regions have to eliminate fossil fuel subsidies and implement energy pricing that reflects both supply costs and local externalities related to fossil fuels? How large are the foregone welfare gains due to the subsidized use of fossil fuels in today's economies, or, put differently, what are the true cost of subsidizing fossil fuels? To what extent would the removal of both explicit and implicit fossil fuel subsidies contribute to helping individual countries and the global community achieve the climate targets outlined in the Paris Agreement?

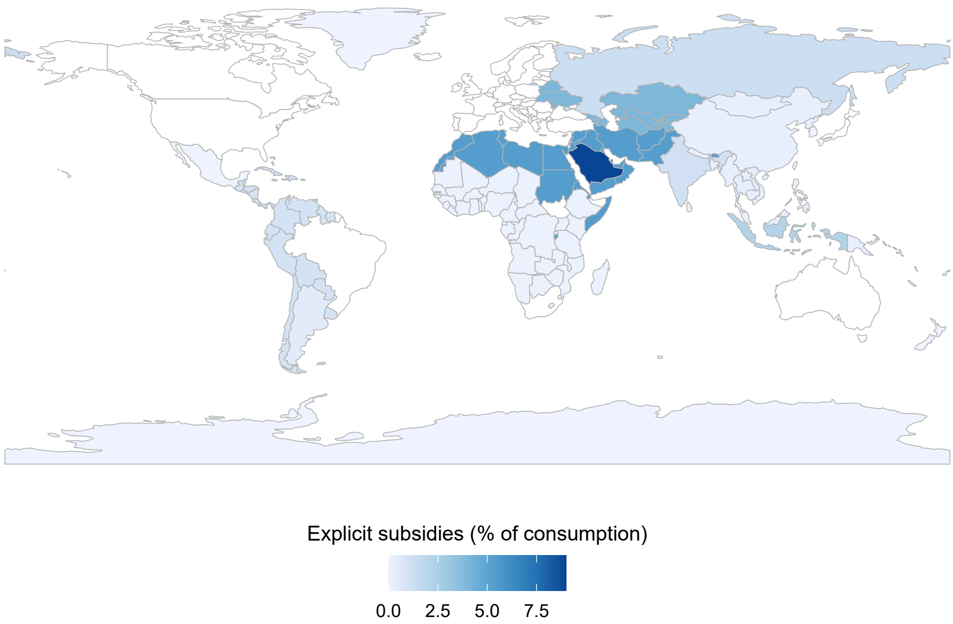
We present the first study on the welfare effects of both explicit and implicit fossil fuel subsidies using a structural general equilibrium model of the global economy, which integrates spatial (i.e., country- and region-specific) and industry-level details of fossil energy supply and consumption. Previous studies have either focused exclusively on explicit fossil fuel subsidies (Jewell et al., 2018; Chepeliev and van der Mensbrugghe, 2020; Arzaghi and Squalli, 2023) or, in the case of implicit subsidies, have relied on partial equilibrium models centered on individual countries' fossil fuel markets (Davis, 2014; Clements et al., 2014; Parry, Veung and Heine, 2015; Breton and Mirzapour, 2016; International Energy Agency, 2017; Coady et al., 2019; Black et al., 2023). In contrast, our analysis incorporates both market and non-market welfare effects of fossil fuel subsidies within a general equilibrium framework.

We provide evidence that a multi-market and international perspective is es-

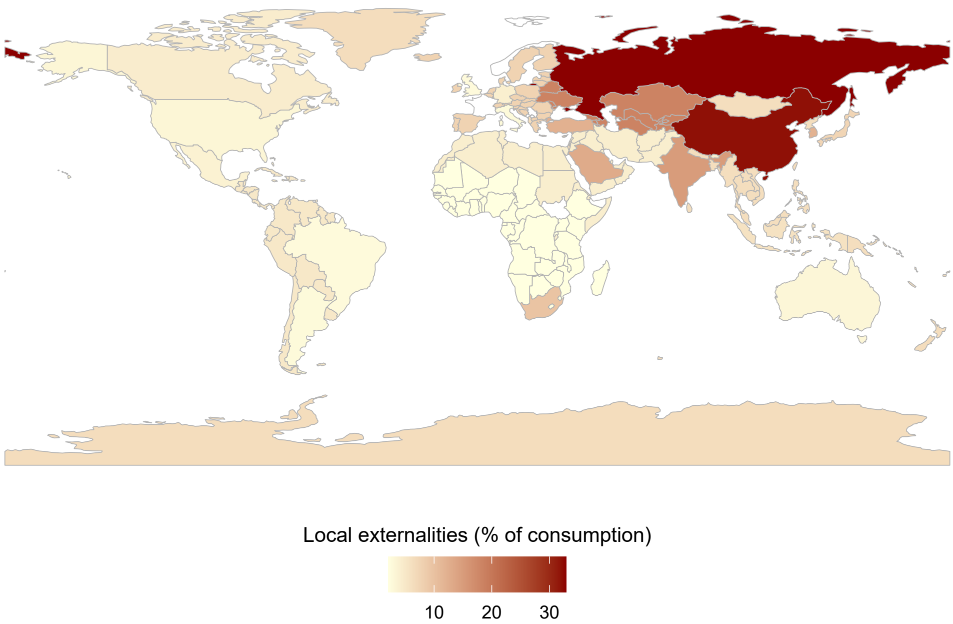
[1]Figure 1 illustrates the regional heterogeneity in explicit and implicit fossil fuel subsidies. We take a closer look at the data in Section III.

[2]Using data on fossil fuel subsidies from the World Bank, Davis (2014) finds that road-sector subsidies for gasoline and diesel totaled \$110 billion in 2012, creating a global deadweight loss of US\$44 billion. When external costs are included, the economic costs rise by US\$32 billion.

Figure 1. Fossil fuel subsidies and major local externalities related to fossil energy use in percent of consumption for selected countries and world regions



(a) Explicit subsidies: Fossil fuel prices below supply cost



(b) Implicit subsidies: Local externalities related to air pollution and oil use in road-based transportation

Notes: Own calculations based on data on explicit fossil fuel subsidies from Chepeliev, McDougall and van der Mensbrugghe (2018), on implicit fossil fuel subsidies from (Coady et al., 2017), and on consumption from GTAP (Aguiar et al., 2022).

sential. Fossil fuels are deeply integrated into the production and consumption of goods and services, both domestically and within global supply chains. Consequently, markets and economies are highly interconnected and responsive to climate and fiscal policy decisions regarding the removal of fossil fuel subsidies. Moreover, the non-market and CO_2 emissions effects of reducing fossil fuel use are closely tied to the physical quantities of coal, oil, and gas. Evaluating fossil fuel subsidies thus requires a framework that captures not only the monetary value of economic activity but also the impact in terms of physical energy flows.

Our structural model integrates detailed data on both explicit and implicit fossil fuel subsidies from the IMF database (Parry et al., 2014; Coady et al., 2017) and the Global Trade Analysis Project (Chepeliev, McDougall and van der Mensbrugghe, 2018; Aguiar et al., 2022), along with national income and product accounts data, including bilateral international flows and trade tariffs. The model accounts for the marginal local external costs of consuming refined oil (e.g., gasoline, diesel, kerosene), coal, and natural gas, differentiating by fuel type, sector of use, and type of local externality. These local externalities include health impacts from elevated mortality risks due to air pollutants—specifically particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), and nitrogen oxides (NO_x)—as well as non-pollutant externalities related to oil use in motor vehicles, such as congestion, accidents, and, to a lesser extent, road damage.

To estimate the welfare effects of explicit and implicit subsidies on fossil fuels, we perform counterfactual analysis using our structural equilibrium model. The factual benchmark is defined by our model, which is calibrated to observed global and country-level production, consumption, and international trade flows, assuming existing explicit subsidies on fossil fuels and unpriced local externalities. The counterfactual experiments adopt the fundamental concept of Pigouvian pricing (Pigou, 1920; Coase, 1960; Baumol and Oates, 1988), defining the full costs of fossil fuels as the price that eliminates both explicit and implicit subsidies. By exploiting the heterogeneity of subsidies across fuel, country, sector, and externality type, as represented in our data and model, we analyze counterfactual experiments with varying scopes of Pigouvian pricing to examine the structure of countries' incentives for subsidy reform.

Our main findings are as follows. First, we present evidence showing that there are strong incentives for countries to unilaterally eliminate both explicit and implicit subsidies on fossil fuels. Our analysis focuses on three key aspects that influence these incentives: the impact on welfare (both market and non-market), the iscal revenues generated by eliminating subsidies, and the impact on the economic costs associated with achieving 2°C-compatible national climate targets under the Paris Agreement. We find that the unilateral removal of explicit fossil fuel subsidies results in modest welfare gains for most countries—averaging 0.2% globally—with more substantial benefits observed in countries with sizable subsidies, such as Saudi Arabia and Indonesia. In contrast, unilateral implementation of local Pigouvian energy pricing—which includes the removal of explicit subsidies—generates significantly larger welfare gains, averaging 3.7% across countries and regions.

Pigouvian pricing produces divergent effects on market and non-market welfare, which means that the net effect is a priori unclear: while the reduction in implicit subsidies enhances non-market welfare, the associated increase in energy prices tends to reduce market welfare. We find the overall net effect to be positive for nearly all countries, particularly in countries with high energy intensity of consumption or high marginal damages. These include major economies such as China, India, Saudi Arabia, Russia, and several European and Commonwealth countries, where welfare improvements range from 5% to 23%. Furthermore, pricing externalities linked specifically to local air pollution captures nearly 90% of these net welfare benefits, underscoring the effectiveness of targeting pollutant-specific reforms. Pricing non-polluting externalities yields greater welfare gains than the removal of explicit subsidies alone.

Fiscal revenue implications are substantial: on average, countries or regions could generate fiscal revenues equivalent to 4.9% of consumption through local Pigouvian energy pricing, with regional estimates ranging from 1.8% to 16.2%. In contrast, the removal of explicit fossil fuel subsidies alone would yield comparatively modest revenues, averaging just 0.4% of consumption annually. Aggregated across all countries and regions, we estimate that total fiscal revenues from comprehensive local Pigouvian pricing would reach 4.9% of global consumption—equivalent to $2.5 trillion per year (in 2017 USD).

Second, while the unilateral removal of explicit fossil fuel subsidies has only a limited effect on the shadow cost of carbon required to meet Paris climate targets, the elimination of implicit subsidies substantially reduces these costs. On average, country-level carbon prices decline by 68%, and about one-third of countries and regions would overachieve their Paris climate targets, effectively reducing the required carbon price to zero. Crucially, the integration of climate policy with local Pigouvian energy pricing lowers the cost of achieving climate goals for all countries and regions. On average, across countries, adding Pigouvian energy pricing on top of carbon pricing to meet the Paris climate target increases welfare by 120% or 1.7 percentage points. The reason is that CO_2 pricing alone represents a cost-effective way to achieve the climate target, but does not take into account the non-market welfare cost created by the local externalities of fossil fuel use. For countries that exceed their climate targets through Pigouvian energy pricing alone, additional climate policy is therefore redundant. For countries that do not meet their climate target through Pigouvian energy pricing alone, the policy combination enhances welfare compared to relying on carbon pricing alone.

Third, we estimate that global CO_2 emissions would decline by 32% if all countries and regions eliminated both explicit and implicit fossil fuel subsidies. Notably, the global implementation of Pigouvian pricing targeting local air pollution externalities alone would result in a 26% reduction in emissions—sufficient to meet the global mitigation requirements consistent with 2°C-compatible targets outlined in the Paris Agreement.

Finally, using our global, multi-region model, we estimate that the welfare cost of the unregulated use of fossil fuels—characterized by the continuation of explicit subsidies and no removal of implicit subsidies—amounts to 2.4% of global consumption. Implementing Pigouvian pricing for local air pollution externalities alone would result in a global welfare improvement of 2.3%. In contrast, the welfare effects of removing explicit fossil fuel subsidies are modest at the global level, yielding an average gain of only 0.1%. Comprehensive local Pigouvian energy pricing is advantageous for all countries and regions, even for those facing welfare losses due to reduced fossil fuel export revenues—provided it is implemented globally.

In sum, our empirical findings provide strong evidence that local Pigouvian energy pricing generates significant welfare gains, substantial fiscal revenues, and first-order climate co-benefits, making it a highly beneficial policy for both unilateral and multilateral adoption. In particular, aside from political economy challenges[3] that may impede the elimination of both explicit and implicit fossi fuel subsidies, our findings suggest that decarbonization efforts sufficient to reduce global CO_2 emissions by one-third could pay for itself.

Our paper contributes to several literatures. First, we provide the first analysis of the welfare effects of both explicit and implicit fossil fuel subsidies using a structural general equilibrium model of the global economy that incorporates country- and industry-level detail in fossil energy supply and use. Prior studies have either focused solely on explicit subsidies (Jewell et al., 2018; Chepeliev and van der Mensbrugghe, 2020; Arzaghi and Squalli, 2023) or used partial equilibrium models to examine implicit subsidies at the national level (Davis, 2014; Clements et al., 2014; Parry, Veung and Heine, 2015; Breton and Mirzapour, 2016; International Energy Agency, 2017; Coady et al., 2019; Black et al., 2023). In contrast, our approach captures both market and non-market welfare effects in a unified general equilibrium framework, providing novel global estimates at the country level.

Second, recent literature has sought to reframe the public good dilemma of climate change by highlighting unilateral incentives for decarbonization. Mitigation policies are shown to yield substantial co-benefits for local air quality and health (Shindell et al., 2018; Huang et al., 2023). Thompson et al. (2014) find that health benefits can offset 26-1,050% of U.S. carbon mitigation costs, while Vandyck et al. (2018) estimate that achieving the Paris Agreement targets could prevent 71,000 to 346,000 premature deaths globally each year.[4] Similarly, Basaglia, Grunau and Drupp (2024) link major pollution reductions in EU industries to the EU ETS and emissions standards. Bilal and Känzig (2025) show that, for major emitters like the US and EU, ambitious decarbonization can be self-financing. While we provide estimates of the non-market welfare costs of fossil fuel use—including both pollution and non-pollution externalities—our primary focus lies elsewhere: we develop a structural, quantitative model capable of analyzing counterfactuals, allowing us

[3] Cutting fossil fuel subsidies has proved extremely difficult, not least because of political economy issues. Subsidies exist often because they are the only reliable mechanism available to governments that are under pressure to provide benefits to politically well-organized groups (Victor, 2009). Inchauste and Victor (2017) provide an in-depth study for four countries to identify barriers to subsidy reform. Droste, Chatterton and Skovgaard (2024) propose a political economy theory of fossil fuel subsidy reforms in OECD countries. Mahdavi, Martinez-Alvarez and Ross (2022) use high-frequency data on gasoline taxes and subsidies for 157 countries and find that fossil fuel taxes are determined by a country's revenue needs, not its political institutions or environmental commitments.

[4] Empirical work shows local air pollutants negatively affect mortality (Knittel, Miller and Sanders, 2016; Jarvis, Deschenes and Jha, 2022), health costs (Schlenker and Walker, 2016), and labor productivity (Bretschger and Komarov, 2024).

to assess how internalizing local externalities can advance progress toward Paris Agreement climate targets. Thus, we reverse the perspective by asking what the climate mitigation co-benefits are of addressing externalities not related to GHG emissions—rather than examining the co-benefits of climate policies themselves. Given the ongoing gridlock in international climate policy, we argue that this perspective is highly relevant.

Third, by adopting a comprehensive welfare perspective that accounts for local externalities beyond GHG emissions, we show that carbon pricing alone may fall short of cost-effectiveness. In doing so, we add to the scarce literature on correlated externalities. In reality, a single source of emissions is typically comprised of multiple pollutants that cause simultaneous localized and global externality problems, and pollution abatement in turn jointly reduces the flows of these pollutants (Caplan and Silva, 2005). Conceptual and theoretical work has explored how the design of environmental regulation should account for the correlation structure between multiple pollutants (Moslener and Requate, 2007; Fullerton and Karney, 2018; Brunel and Johnson, 2019).[5] Despite the centrality of externalities in environmental economics, there is surprisingly little quantitative research on the welfare effects of policies targeting correlated externalities. The case of CO_2 emissions and local externalities associated with fossil fuel consumption, both based on the same underlying combustion activity, is a prime example of correlated externalities. We use our structural model to examine whether pricing local externalities offers greater welfare benefits than directly combating carbon externalities. Again, given the gridlock surrounding international carbon pricing as a global approach to climate policy, this question holds significant policy importance.

This paper proceeds as follows. Section I describes our model and defines concepts for local Pigouvian energy pricing. Section II describes data sources and model calibration. Section III provides a descriptive analysis of fossil energy subsidies and local externalities using the observational data which underlies our structural model. Section IV presents our design of counterfactual experiments and scrutinizes the role international trade and global supply chains for assessing the removal of fossil fuel subsidies. Section V presents and discusses our main results. Section VI concludes. An online appendix provides further details on the model implementation and results.

I. The Model

A. Measuring Welfare and Emissions

Our welfare assessment is based on a comprehensive global general equilibrium framework that accounts for domestic production and consumption responses as well as international market effects resulting from local energy pricing reforms. Equilibrium prices $\boldsymbol{p}$ and quantities $\boldsymbol{q}$ are derived from a multi-region, multi-sector

[5]Another, less closely related strand of literature explores how environmental taxes interact with fiscal externalities stemming from pre-existing distortions in factor markets and broader fiscal policies (Goulder et al., 1999; Parry and Williams, 1999; Barrage, 2020).

general equilibrium model that treats policy decisions regarding explicit and implicit fossil fuel subsidies as given.

The regulator in region $r \in \mathcal{R}$ has two ways to directly influence local fossil fuel prices: reducing existing fossil fuel subsidies $\boldsymbol{s}$ and levying taxes $\boldsymbol{\tau}$ to address local externalities related to fossil fuel use. Subsidies are paid for the use of fossil fuel of type $f \in \mathcal{F} = \{\mathit{Coal}, \mathit{Natural\ gas}, \mathit{Oil}\}$ used in sector $g \in \mathcal{G}$, where $\mathcal{G}$ comprises all production sectors and final consumption activities. Similarly, taxes on the use of fossil fuel are differentiated by fuel type and sector and, in addition, by the type of local externality $x \in \mathcal{X} = \mathcal{L} \cup \mathcal{N}$, which include damages related to local air pollution $\mathcal{L} = \{SO_2, NO_x, PM_{2.5}\}$ and local (non-pollutant) externalities related to oil use in transportation $\mathcal{N} = \{\mathit{Congestion}, \mathit{Accidents}, \mathit{Road\ damages}\}$. Let $\boldsymbol{s}$ and $\boldsymbol{\tau}$ denote the vectors of externality-, fuel-, sector-, and region-specific taxes and subsidies on fossil energy, respectively, with elements:

$$\tau_{xfgr} \in (\mathcal{X} \times \mathcal{F} \times \mathcal{G} \times \mathcal{R}) \quad \text{and} \quad s_{fgr} \in (\mathcal{F} \times \mathcal{G} \times \mathcal{R})\,.$$

Welfare W_r in region r comprises the economic and non-economic costs and benefits from local energy pricing reform $\boldsymbol{\tau}$ and $\boldsymbol{s}$ (enacted in region r and possibly in other regions):

$$(1) \qquad W_r := \underbrace{U_r(C_r[\boldsymbol{q}(\boldsymbol{\tau},\boldsymbol{s}),\boldsymbol{p}(\boldsymbol{\tau},\boldsymbol{s})])}_{\substack{\text{Market effects:}\\ \text{Utility from}\\ \text{private consumption}}} - \underbrace{\sum_{x\in\mathcal{X}} D_{xr}[\boldsymbol{q}(\boldsymbol{\tau},\boldsymbol{s}),\boldsymbol{p}(\boldsymbol{\tau},\boldsymbol{s})]}_{\substack{:=D_r,\ \text{Non-market effects:}\\ \text{Damages from multiple}\\ \text{local externalities}}}\,,$$

where U_r measures local economic welfare (excluding damages from local externalities) in money metric utility based on the equilibrium level of private consumption C_r of the representative consumer in region r.

D_{rx} denotes monetized damages due to the local externality x in region r as a function of the equilibrium quantity of fossil fuels used in local production and consumption:

$$(2) \qquad D_{xr} := \sum_{f\in\mathcal{F},g\in\mathcal{G}} \overline{m}_{xfgr} \times q_{fgr}^{\mathit{Fossil\ energy\ used}}[\boldsymbol{q}(\boldsymbol{\tau},\boldsymbol{s}),\boldsymbol{p}(\boldsymbol{\tau},\boldsymbol{s})]\,.$$

$\overline{m}_{xfgr}$ denotes the externality-, fuel-, sector-, and region-specific monetized marginal external cost per unit of fossil energy used. We assume that $\overline{m}_{xfgr}$ is constant, i.e. marginal external costs are independent of the quantity of fossil energy used.[6] In addition to the value-based economic model, our framework incorporates supplementary physical accounting of energy flows to enable the measurement of local external costs as a function of physical energy volumes $q_{fgr}^{\mathit{Fossil\ energy\ used}}$ consistent with economic equilibrium decisions.

[6]Given the global, multi-sector, and multi-fuel scope of this study, the assumption of constant external marginal costs is dictated by data availability. While empirical estimates of non-linearities in fossil fuel-related externality costs exist for some countries, the IMF database used in our analysis provides only point estimates of marginal costs.

The climate co-benefits from local energy pricing are evaluated by observing the development of global CO_2 emissions from the burning of fossil fuels:[7]

$$(3) \qquad \sum_{r\in\mathcal{R}} CO2_r = \sum_{f\in\mathcal{F},g\in\mathcal{G}} \bar{e}_{fgr} \times q_{fgr}^{\textit{Fossil energy used}}[\boldsymbol{q}(\boldsymbol{\tau},\boldsymbol{s}),\boldsymbol{p}(\boldsymbol{\tau},\boldsymbol{s})]$$

where $\bar{e}_{fgr}$ denotes the fuel-, sector-, and region-specific benchmark CO_2 intensity (per unit of fossil energy).

B. Local Energy Pricing

Fossil fuels serve as inputs in both local production and consumption activities. Energy subsidies and taxes are applied on an ad valorem basis at the point of combustion, whether in production (e.g., coal-fired electricity generation) or consumption (e.g., refined oil for transportation or natural gas for residential heating).

Output of sector g in region r, Y_{gr}, is produced using a nested constant-elasticity-of-substitution (CES) technology which combines inputs of capital K_{gr}, natural energy resource of type N_{zgr} of type $z \in \mathcal{Z} = \{\textit{Coal}, \textit{Natural gas}, \textit{Crude oil}\}$, labor L_{gr}, a composite of energy inputs E_{gr}, and a composite of intermediate inputs from other (non-energy) sectors O_{gr} (Figure C.2 in the Online Appendix illustrates the nested structure):

$$(4) \qquad Y_{gr} = F_{gr}[G(\underbrace{H(K_{gr},L_{gr})}_{\text{Value-added composite}}, \underbrace{E_{gr}(A_{i\in\mathcal{F}gr})}_{\text{Energy composite}}), \underbrace{O_{gr}(A_{i\notin\mathcal{F}gr})}_{\text{Non-energy composite}}, \underbrace{N_{zgr}}_{\text{Natural resource of fossil energy}}].$$

Each intermediate input A_{igr}, $i \in \mathcal{I}$, is an aggregation of goods produced at different locations, i.e. domestically produced and imported varieties of the same commodity i (Armington, 1969). Local energy taxes and subsidies drive a wedge between the price paid by fossil energy users and the (net-of-tax or -subsidy) price charged by fossil energy suppliers. Local supply cost (including value-added tax) for domestically-produced and imported fossil fuels of type f are p_{fr}^Y and p_{fr}^M, respectively, and

$$(5) \qquad \hat{p}_{fgr}^Y = p_{fr}^Y(1-s_{fgr}^Y) \quad \text{and} \quad \hat{p}_{fgr}^M = p_{fr}^M(1-s_{fgr}^M)$$

denote the supply cost taking into account existing fossil fuel subsidies $\boldsymbol{s} = \{s_{fgr}^Y, s_{fgr}^M\}$. The user cost (per unit of energy) of fossil fuel f in sector g and region r, c_{fgr}^A, which

[7]Our analysis focuses on the climate benefits derived from reducing CO_2 emissions resulting from the combustion of fossil fuels. It is beyond the scope of this paper to address the inclusion of non-CO_2 GHG emissions and process emissions. In the context of examining the local co-benefits of climate policy, non-CO_2 emissions have been explored in previous studies, such as those by Vandyck et al. (2018) and Anenberg et al. (2012).

includes fossil fuel subsidies and taxes to address local externalities, is given by:

$$(6)\quad c^A_{fgr} = \underbrace{(1 + \sum_{x\in\mathcal{X}} \tau_{xfgr} + \delta_r \overline{e}_{fgr})}_{\text{Local energy taxes to address local externalities and costs of carbon}} \times \underbrace{\left[\theta^D_{fgr}(\hat{p}^Y_{fgr})^{1-\sigma^A_{fr}} + (1-\theta^D_{fgr})(\hat{p}^M_{fgr})^{1-\sigma^A_{fr}}\right]^{\frac{1}{1-\sigma^A_{fr}}}}_{\equiv \hat{p}^A_{fgr}\text{, Local energy market price including fossil fuel subsidies (for domestic and imported varieties)}}$$

where θ^D_{fgr} and σ^A_{fr} denote share and substitution parameters used in the Armington aggregation, respectively. δ_r is a regional carbon surcharge paid in proportion to the carbon content of the fossil fuel used.

Following the definition of Coady et al. (2017), an explicit energy subsidy corresponds to a situation where the user cost of fossil energy is below its supply cost.

DEFINITION 1: ***(Explicit subsidies)*** *An explicit energy subsidy for fossil fuel f used in sector g in region r involves either $s^Y_{fgr} > 0$, $s^M_{fgr} > 0$, or both.*

An implicit energy subsidy refers to the situation in which consumers face a price for fossil energy that does not fully reflect the supply cost and the local and global external damages of energy use. We define the local Pigouvian energy price as the price that reflects the local costs but ignores the global costs from CO_2 emissions:

DEFINITION 2: ***(Local Pigouvian energy prices)*** *The local price of fossil fuel f used in sector g in region r fully reflects the supply cost and external damages associated with the presence of multiple fossil-energy related local externalities, i.e. the user cost of fossil energy c^A_{fgr} involves local externality taxes $\tau_{xfgr} = \overline{m}_{xfgr}$ and the removal of explicit energy subsidies $s^Y_{fgr} = s^M_{fgr} = 0$.*

The local Pigouvian energy price thus expresses how energy use should be priced according to the self-interest of a country or region.

The "full" Pigouvian price on energy would, in addition, reflect the global climate externality (i.e., as reflected by the social cost of carbon). Given the conceptual and empirical challenges associated with determining the social cost of carbon, particularly in the context of multiple countries, we refrain from employing theoretical "full" Pigouvian pricing. Instead, we adopt an alternative approach, using the CO_2 emissions reduction targets, or Nationally Determined Contributions (NDCs), established by countries under the Paris Agreement, and calculate the national carbon price π_r required to meet those targets. To this end, we introduce regional carbon markets, represented by (15), in our model with scaled NDCs as regional limits on CO_2 emissions. We can then define:

DEFINITION 3: ***(Emissions-constrained Pigouvian energy prices)*** *In addition to local Pigouvian energy pricing ($\tau_{xfgr} = \overline{m}_{xfgr}$ and $s^Y_{fgr} = s^M_{fgr} = 0$), CO_2 emissions from local energy use are priced to meet national climate targets ($\delta_r = \pi_r$).*

C. *Global Supply Chains, International Trade, and Markets*

To measure the welfare effects from removing explicit and implicit subsidies on fossil fuels in the global economy, we use a multi-region multi-sector Arrow-Debreu general equilibrium model which resolves global supply chains as portrayed by a multi-regional input-output structure and bi-lateral commodity-specific international trade flows. The model captures the behavioral responses of firms and consumers in multiple regions to local energy prices. Local and global damages from fossil fuel use beyond what is reflected in local energy prices are treated as externalities, i.e. economic agents ignore these effects.[8]

DOMESTIC PRODUCTION AND FINAL GOOD AGGREGATION.—Product and factor markets are perfectly competitive, and there is free entry and exit. When portraying the decentralized optimization problems of price-taking economic agents, we can thus characterize optimal input choices as arising from cost (expenditure) minimization subject to technical constraints.

The representative firm in sector Y_{gr} takes the output price p^Y_{gr} and input prices for capital p^K_r, labor p^L_r, natural resources p^N_{zgr}, and intermediate inputs p^A_{igr} as given, and maximizes profits according to:

$$\max_{K_r, L_r, \boldsymbol{A_{gr}}, \boldsymbol{N_{gr}}} \quad \Pi^Y_{gr} = p^Y_{gr} Y_{gr} - p^K_r K_{gr} - p^L_r (1 + \tau^L_{gr}) L_{gr} - \sum_{i \in \mathcal{I}} p^A_{igr} A_{igr} - \sum_{z \in \mathcal{Z}} p^N_{zr} N_{zgr}$$

subject to the technology constraint (4). τ^L_{gr} denotes a country- and sector-specific tax rate on labor earnings used in sector g and region r.

In equilibrium, the unit cost in each sector are greater or equal to the output price, and firms make zero profits. The zero-profit condition for Y_{gr} is then given by:

$$c^Y_{gr}(\boldsymbol{p(\tau, s)}, \boldsymbol{\theta}, \boldsymbol{\sigma}) \geq p^Y_{gr} \quad \perp \quad Y_{gr} \geq 0\,. \tag{7}$$

Marginal supply costs c^Y_{gr} depend on input prices $\boldsymbol{p(\tau, s)}$ and technology parameters $\boldsymbol{(\theta, \sigma)}$. Production activities are represented by nested CES technologies (see (4) and Figure C.2). $\boldsymbol{\theta}$ comprises the value shares for each input at a given sub-nest of the nested production function. For example, the value share of fossil energy input f in the energy composite E_{gr} is given by:

$$\theta^A_{fgr} = \frac{\overline{p}^A_{fgr} \overline{A}_{fgr}}{\sum_{f'} \overline{p}^A_{f'gr} \overline{A}_{f'gr}} \tag{8}$$

where $\overline{p}^A$ and $\overline{A}$ are prices and quantities (or $\overline{p}^A \times \overline{A}$ the value) observed at the

[8] We characterize the interactions of decentralized decisions by consumers and producers by formulating a mixed complementarity problem which associates quantities with zero-profit and prices with market-clearing conditions (Mathiesen, 1985; Rutherford, 1995). A characteristic of the Arrow-Debreu model is that it can be cast as a complementary problem, i.e. given a function $F\colon \mathbb{R}^n \longrightarrow \mathbb{R}^n$, find $z \in \mathbb{R}^n$ such that $F(z) \geq 0$, $z \geq 0$, and $z^T F(z) = 0$, or, in short-hand notation, $F(z) \geq 0 \perp z \geq 0$. Intuitively, complementarity means that if $z > 0$ then $F(z) = 0$ and if $F(z) > 0$ then $z = 0$.

benchmark. $\boldsymbol{\sigma}$ comprises the elasticity of substitution parameters between inputs at each sub-nest. For example, σ^E_{gr} denotes the elasticity of substitution between fossil fuels and electricity in the energy composite E_{gr}.

Differentiating the unit cost function with respect to input prices yields the demand for inputs. For example, the optimal input choice of fossil energy f in sector Y_{gr} is given by:

$$A_{fgr} = Y_{gr} \frac{\partial c^Y_{gr0}(\boldsymbol{p}(\boldsymbol{\tau}, \boldsymbol{s}), \boldsymbol{\theta}, \boldsymbol{\sigma})}{\partial p^A_{fgr}} \,. \tag{9}$$

For reasons of a compact algebraic model representation, we avoid explicitly writing out optimization problems, cost functions, and input demands, for each production and consumption activity.[9] Instead, we state for each activity the technology parameters and corresponding zero-profit condition. For sector Y_{gr}, technology parameters include:

$$\boldsymbol{\theta^Y} = \{\theta^A_{igr}, \theta^E_{gr}, \theta^v_{gr}, \theta^K_{gr}, \theta^L_{gr}, \theta^N_{zgr}, \theta^{ve}_{gr}, \theta^O_{gr}, \theta^D_{igr}\}$$

which denote the cost shares of Armington input i, energy composite, value-added composite, capital input, labor input, natural resource input z, value added and energy composite, composite of non-energy intermediate inputs, domestic variety of type i, respectively, and:

$$\boldsymbol{\sigma^Y} = \{\sigma^Y_{gr}, \sigma^{va}_{gr}, \sigma^E_{gr}, \sigma^{KL}_{gr}, \sigma^O_{gr}, \sigma^D_{gr}\}$$

which denote the elasticity of substitution parameters at the top-nest, between value added and energy composites, between inputs in energy composite, between capital and labor, between inputs in non-energy composite, between domestic and imported variety of type i, respectively.

In addition to sectoral production activities, the g set includes the aggregation of goods for final demand purposes which are: private consumption ($g = C$), public consumption ($g = G$), and investment ($g = I$). For private consumption, $F_{Cr}()$ in (4) defines the utility function for the representative consumer in region r which aggregates final goods:

$$U_{Cr} = F_{Cr}[A_{1Cr}, \ldots, A_{iCr}, \ldots, A_{ICr}] \,. \tag{10}$$

ARMINGTON AGGREGATION AND INTERNATIONAL TRADE.—All goods, except final goods for consumption and investment purposes, are tradable. Following the (Armington, 1969) approach, varieties of the same good are distinguished by origin (i.e. place of production) according to a two-stage differentiation (see Figure C.2 in the Online Appendix).

[9]This would only add tedious algebra without additional insight. In general, if the production technology is CES with inputs x_i, $y = f(x) = \overline{y}[\sum_i \theta_i (x_i/\overline{x}_i)^\rho]^{1/\rho}$, the unit cost function in calibrated share form (Rutherford, 2002) is $c(p) = \overline{c}[\sum_i \theta_i (p_i/\overline{p}_i)^{1-\sigma}]^{1/(1-\sigma)}$ where σ denotes the elasticity of substitution and the value share of input i is defined as: $\theta_i = \overline{p}_i \overline{x}_i / (\sum_{i'} \overline{p}_{i'} \overline{x}_{i'})$, where $\sum_i \theta_i = 1$.

At the first stage, imports from different regions are aggregated. The equilibrium level of aggregate imports of good i in region r, M_{ir}, is determined by:

$$c_{ir}^M = \left(\sum_{r'} \theta_{ir'r}^M (p_{ir'}^Y)^{(1-\sigma_{ir}^M)}\right)^{1/1-\sigma_{ir}^M} \geq p_{ir}^M \quad \perp \quad M_{ir} \geq 0\,. \tag{11}$$

where $\theta_{ir'r}^M$ denotes the benchmark cost share of exports of good i from region $r' \in \mathcal{R}$ to region r in total imports of region r, and σ_{ir}^M is the elasticity of substitution for good i for imports of region r from other regions.

At the second stage, aggregate imports are combined with domestically-supplied varieties of the same good, thereby introducing preferences for like goods produces at home and abroad. Using the definition of the unit cost from (6), the equilibrium quantity of the Armington aggregate of good i, which is supplied for the use in sector Y_{gr}, is determined by:

$$c_{igr}^A \geq p_{igr}^A \quad \perp \quad A_{igr} \geq 0\,. \tag{12}$$

SMALL OPEN ECONOMY.—We implement an alternative international trade closure that assumes that regions or countries behave according to a small-open-economy (SOE) assumption in international markets, i.e. each region takes the international world market prices of imports and exports as given. Comparing the SOE with a full multi-region trade model allows for an assessment of international market responses to subsidy removal and the pricing of local externalities. In the case of the SOE trade closure, (11) and (13a) change to, respectively:

$$c_{ir}^M = p_i^{World} \geq p_{ir}^M \quad \perp \quad M_{ir} \geq 0 \tag{11'}$$

$$Y_{ir} \geq \sum_g A_{igr} \frac{\partial c_{igr}^A}{\partial p_{ir}^Y} + M_i^{World} \frac{\partial c_i^{M,World}}{\partial p_{ir}^Y} \quad \perp \quad p_{ir}^Y \geq 0 \tag{13a'}$$

where p_i^{World} denotes the world market price for good i, M_i^{World} the total imports of good i by the rest of the world, and $c_i^{M,World}$ the unit import cost of the rest of the world.

MARKETS.—Market clearance conditions for goods and factor markets determine equilibrium prices. The market for sectoral good Y_{igr}, Armington good A_{igr}, and the aggregate import composite M_{ir}, respectively, clears if:

$$Y_{ir} \quad \geq \quad \sum_g A_{igr} \frac{\partial c_{igr}^A}{\partial p_{ir}^Y} + \sum_{r'} M_{ir'} \frac{\partial c_{ir'}^M}{\partial p_{ir}^Y} \quad \perp \quad p_{ir}^Y \geq 0 \tag{13a}$$

$$A_{igr} \quad \geq \quad Y_{gr} \frac{\partial c_{gr}^Y}{\partial p_{igr}^A} \quad \perp \quad p_{igr}^A \geq 0 \tag{13b}$$

$$M_{ir} \;\; \geq \;\; \sum_g A_{igr} \frac{\partial c^A_{igr}}{\partial p^M_{ir}} \quad \perp \quad p^M_{ir} \geq 0\,. \tag{13c}$$

Labor and capital are perfectly mobile between sectors within a region, but immobile across regions. The wage rate and capital rental rate for the respective regional market in region r is determined by:

$$\overline{L}_r \;\; \geq \;\; \sum_g Y_{gr} \frac{\partial c^Y_{gr}}{\partial p^L_r} \quad \perp \quad p^L_r \geq 0 \tag{14a}$$

$$\overline{K}_r \;\; \geq \;\; \sum_g Y_{gr} \frac{\partial c^Y_{gr}}{\partial p^K_r} \quad \perp \quad p^K_r \geq 0 \tag{14b}$$

where the $\overline{L}_r$ and $\overline{K}_r$ are the exogenously given endowments of labor and capital owned by the household in region r. Similarly, the market for the fossil energy resource z in region r is in equilibrium if:

$$\overline{N}_{zr} \geq \sum_g Y_{gr} \frac{\partial c^Y_{gr}}{\partial p^N_{zr}} \quad \perp \quad p^N_{zr} \geq 0 \tag{14c}$$

where $\overline{N}_{zr}$ is the natural resource endowment owned by the household in region r.

REGIONAL CARBON MARKETS.—For analyzing regional limits on CO_2 emissions $\overline{CO2}^{NDC}_r$ (as, for example, implied by the NDCs under the Paris agreement), we include the possibility of regional carbon markets:

$$\overline{CO2}^{NDC}_r \geq \sum_g \sum_f \overline{e}_{fgr} A_{fgr} \quad \perp \quad \pi_r \geq 0 \tag{15}$$

where π_r is the regional carbon price and $\overline{CO2}^{NDC}_r$ measured in physical quantities (CO_2 equivalents).

FINAL DEMANDS.—Households in region r receive income from inelastically supplying capital, labor, and natural resource endowments, collecting tax revenues Γ_r (including potential carbon revenues and net of subsidy payments):

$$\Omega_r = p^K_r \overline{K}_r + p^L_r \overline{L}_r + \sum_z p^Z_{zr} \overline{N}_{zr} + \Gamma_r + \overline{\Delta}_r$$

where $\overline{\Delta}_r$ is the balance of payment deficit or surplus in region r in the benchmark, and where $\sum_r \Delta_r = 0$. Throughout our analysis, we assume that the revenues from pricing local external effects and from carbon pricing are returned to the representative consumer in each region as a lump sum (included in Γ_r). Equilibrium on the market for private consumption requires that:

$$p^Y_{Cr} Y_{Cr} = \Omega_r\,. \tag{16a}$$

Demands for public consumption and aggregate investment are treated as exogenous and invariant to climate policy choices, given by respective benchmark levels $\overline{G}_r$ and $\overline{I}_r$ in each region. Markets clear if:

$$p^Y_{Gr} Y_{Gr} = \overline{G}_r \quad \text{and} \quad p^Y_{Ir} Y_{Ir} = \overline{I}_r \,. \tag{16b}$$

COMPETITIVE EQUILIBRIUM.—Given policy choices for energy subsidies and taxes $(\boldsymbol{s}, \boldsymbol{\tau})$, the equilibrium is characterized by prices and quantities $(\boldsymbol{p}, \boldsymbol{q})$ such that (i) Y_{gr}, M_{ir}, and A_{igr} maximize profits or minimize costs as in (7), (11), and (12) and (ii) p^Y_{ir}, p^A_{igr}, p^M_{ir}, p^L_r, p^K_r, p^N_{zr}, and p^Y_{Cr} clear the respective markets (13a)–(16b).

II. Data and Calibration

To develop a quantitative version of our theory, a large number of region- and sector-specific parameters have to be determined. We proceed in four steps. First, we characterize the sectoral production structure, intermediate inputs, consumption, and bi-lateral international trade patterns of each regional economy consistent with observed Social Accounting Matrix data describing a benchmark equilibrium at a given base year. This enable us to infer value flows for quantity variables and share parameters $\boldsymbol{\theta} = \{\theta^A_{igr}, \theta^E_{gr}, \theta^v_{gr}, \theta^K_{gr}, \theta^L_{gr}, \theta^N_{zgr}, \theta^{ve}_{gr}, \theta^O_{gr}, \theta^D_{igr}, \theta^M_{ir'r}, \theta^D_{igr}\}$. We also describe the underlying physical accounting of energy flows and how we choose elasticity of substitution parameters in production and consumption $\boldsymbol{\sigma} = \{\sigma^Y_{gr}, \sigma^{va}_{gr}, \sigma^E_{gr}, \sigma^{KL}_{gr}, \sigma^O_{gr}, \sigma^D_{gr}, \sigma^M_{ir}, \sigma^A_{ir}\}$. Second, we detail how we calibrate the model to incorporate data on existing fossil fuel subsidies $\{s^Y_{fgr}, s^M_{fgr}\}$. Third, we describe how we derive estimates for externality-, fuel-, sector-, and region-specific (monetized) marginal external cost per unit of fossil energy used $\overline{m}_{xfgr}$. Fifth, we describe how we translate the regional climate targets as declared by the NDCs under the Paris agreement into the context of our model.

A. *Matching National Income and Product Accounts*

The parametrization of the multi-sectoral economic structure for each region as well as the trade linkages between regions are based on regional social accounting matrix (SAM) data. This study makes use of SAM data from the Global Trade Analysis Project (GTAP, Aguiar et al., 2022) which provides a consistent set of global accounts of production, consumption, and bilateral trade as well as physical energy flows differentiated by primary and secondary energy carrier, including information on existing taxes and subsidies. We use version 11 of the GTAP database and the base year 2017.

Table 1 shows the sectors and commodities, regions, and primary factors of the model. The model distinguishes five energy sectors (coal, natural gas, crude oil, refined oil, electricity) and the services sector which are direct aggregations of the 65 commodities in the GTAP data. Primary factors in the dataset include capital and labor, and fossil energy resources of coal, crude oil, and natural gas. The 141 countries and regions in GTAP11 are presented by 19 countries and 6 region aggregates in our model.

Table 1. Model sectors, regions, and primary production factors

Sectors and commodities ($g \in \mathcal{G}$)	**Countries and regions** ($r \in \mathcal{R}$)
Energy sectors ($i \in \mathcal{I}$)	Argentina (ARG), Australia (AUS),
Coal	Brazil (BRA), Canada (CAN), China (CHN),
Crude oil	France (FRA), Germany (DEU), India (IND),
Natural gas	Indonesia (IDN), Italy (ITA), Japan (JPN),
Refined oil products	Mexico (MEX), Russia (RUS), Saudi Arabia (SAU),
Electricity	South Afria (ZAF), Korea (KOR), Turkey (TUR),
	United Kingdom (GBR), United States (USA),
Energy-intensive & trade-exposed sectors ($i \in \mathcal{I}$)	Rest of Middle East and North Africa (RMEN),
Non-ferrous metals	Rest of Sub-Saharan Africa (RSSA),
Iron and steel	Rest of Commonwealth of Independent States (RCIS),
Non-metallic minerals	Rest of Emerging and Developing Asia (REDA),
Chemicals and rubber	Rest of Latin America and the Caribbean (RLAC),
Paper, pulp, and print	Rest of the World (ROTW), Rest of Europe (REU)
Transport sectors	
Air transport	**Primary factors**
Water transport	Capital
Other transport	Labor
Other sectors	*Fossil energy resources* ($z \in \mathcal{Z}$)
Agriculture	Coal
All other goods	Crude oil
	Natural gas
Final demand	
Private consumption ($g = C$)	
Public consumption ($g = G$)	
Investment ($g = I$)	

Notes: Sectoral and regional classifications shown above are direct aggregations of the 65 sectors and 141 countries/regions contained in the GTAP11 database (Aguiar et al., 2022). The regional mapping is based on Coady et al. (2017). The sectoral and regional mappings are available on request from the authors.

We follow the standard calibration procedure in multi-sectoral numerical general equilibrium modeling (see, for example, Rutherford, 1995; Harrison, Rutherford and Tarr, 1997; Böhringer, Carbone and Rutherford, 2016) according to which production and consumption technologies are calibrated to replicate a single-period reference equilibrium consistent with the SAM data in the base year.[10]

B. Physical energy flows and CO_2 emissions

We make use of data on physical energy flows of domestic and imported energy use by fossil fuel by sector by region $\overline{ev}_{fgr}$ contained in the GTAP11 database. We can then track how physical energy quantities (in mtoe, million tonnes of oil equivalent) change in equilibrium, as is required for our welfare measurement of damages D_{xr} in (2), according to: $q_{fgr}^{\textit{Fossil energy used}} = \overline{ev}_{fgr} \times A_{fgr}$. Similarly, we use GTAP11 data on benchmark CO_2 emissions intensity of domestic and foreign fuels by sector $\overline{e}_{fgr}$ to compute equilibrium CO_2 emissions as in (3).

[10]For example, the CES production technology for output of sector i in region r can be globally characterized, given the elasticity of substitution and observed benchmark *values* for output and inputs from the SAM data, by calibrating the function coefficients according to the value share of inputs for the corresponding unit cost function. A more detailed explanation can be found in, for example, Rutherford (2002).

C. Substitution Elasticities

The choice of values for the elasticity of substitution parameters $\boldsymbol{\sigma}$ follows closely the MIT EPPA model (Paltsev et al., 2005; Chen et al., 2015), a numerical general equilibrium model which has been widely used for climate policy analysis. We use the econometrically estimated substitution parameters parameters for Armington trade provided by Narayanan, Badri and McDougall (2012); σ_{ir}^{M} and σ_{ir}^{A} vary between 1.9-6 depending on region and commodity.

D. Fossil Fuel Subsidies

For explicit fossil fuel subsidies, we use data from the Global Trade Analysis Project (GTAP, Aguiar et al., 2022). Starting from version 11, GTAP already includes explicit consumer subsidies for fossil fuels in the commodity-specific tax rates following the procedure outlined in Chepeliev, McDougall and van der Mensbrugghe (2018). Energy subsidies in the GTAP11 dataset are derived from data provided by the International Energy Agency (IEA).[11]

Using region and fossil fuel specific external data on energy subsidies (in billion \$) provided by GTAP, we compute subsidy rates $\boldsymbol{s} = \{s_{fgr}^{Y}, s_{fgr}^{M}\}$ which are used in (5). The subsidies considered are (i) related to fossil fuels, (ii) levied on consumers, and (iii) are determined by a price-gap approach such that consumer prices are below supply costs (i.e. international market prices in case of traded goods). Thus producer support measures like tax reliefs for coal production are not included. However, since producer subsidies are estimated to be relatively small (Coady et al., 2017), we do not expect that including them would significantly change our results.

E. Local Externalities

We use data collected by the International Monetary Fund (IMF) on local externalities from Parry et al. (2014) and Coady et al. (2017). Data is available in great detail for 155 countries for 2013 and 2015 with marginal external costs of consumption of gasoline, diesel, kerosene, coal, and natural gas by externality. We take into account the following types of local externalities related to fossil energy consumption. Parry et al. (2014) provide a comprehensive account of the methodology for estimating health damages from local air pollutants and non-pollutant externalities of oil use in transportation. Since we draw directly on their data, we include their documented methodology below, quoting text from Parry et al. (2014) to ensure clarity and completeness.

LOCAL AIR POLLUTANTS (LPOLL).—According to (Parry et al., 2014), the estimation procedure comprises four main steps: "(1) Determining how much pollution is inhaled by exposed populations, both in the country where emissions are released

[11]Both the IEA and the IMF utilize a price-gap approach to quantify explicit subsidies, where the international market price is treated as the supply cost. However, there is a key difference in their methodologies: the IMF excludes taxes from its supply cost estimates, thereby capturing only pre-tax fossil fuel subsidies. In contrast, the IEA includes value-added taxes in its reference prices when these taxes are applied to final energy sales, using them as a proxy for economy-wide taxation.

and, for emissions released from tall smokestacks, in countries to which pollution may be transported; (2) Assessing how this pollution exposure affects mortality risks, accounting for factors, such as the age and health of the population, that affect vulnerability to pollution-related illness; (3) Monetizing the health effects; (4) Expressing the resulting damage per unit of fuels. The main cause of mortality risk from pollution is particulate matter with diameter up to 2.5 micrometers ($PM_{2.5}$), which is small enough to permeate the lungs and bloodstream. $PM_{2.5}$ can be emitted directly as a primary pollutant from fuel combustion, but is also produced as a secondary pollutant from chemical reactions in the atmosphere involving primary pollutants, the most important of which is sulfur dioxide (SO_2), but also nitrogen oxides (NO_x)."

NON-POLLUTANT EXTERNALITIES OF OIL USE IN TRANSPORTATION (NPOLL).—Non-pollutant externalities include the following categories according to (Parry et al., 2014): "(1) congestion cost, i.e. the cost of reduced travel speeds for other road users caused by an extra kilometer of driving by one vehicle, averaged across different roads in a country and across times of day; (2) accident cost, i.e. the total societal costs from road traffic accidents; and (3) road damage cost, i.e. vehicle use causes an additional adverse side effect through wear and tear on the road network. However, given that road damage is a rapidly rising function of a vehicle's axle weight, nearly all of the damage is attributable to heavy-duty vehicles."

F. 2°C Compatible Paris Climate Targets

We translate percentage reduction targets, NDCs, submitted by countries to the UNFCCC into effective, 2°C-compatible reduction targets for CO_2 from fossil fuel combustion relative to our model base year of 2017. This involves various steps which include (1) adjusting the data for our own baseline and relative to the model base-year 2017, (2) adjusting the targets to CO_2-only emissions and treating negative targets as well as NDCs expressed as intensity targets, and (3) scaling the (translated) NDCs targets to be consistent with a 2°C global warming temperature target. The Online Appendix provides a detailed description of our approach to translate NDCs to the context of our model. Applying these percentage reduction targets to the region's benchmark CO_2 emissions yields the effective emissions limits $\overline{CO2}_r^{NDC}$ which determine the emissions budgets of regional carbon markets in (15).

III. A First Look at the Data

We first provide a descriptive analysis of the economic magnitude and composition of fossil fuel subsidies and local externalities using the observational data that underpins our counterfactual equilibrium analysis.

Figure 2 shows the breakdown of global explicit and implicit subsidies by fuel and externality. Coal has no explicit subsidies, but its SO_2 emissions are the largest pollutant externality. Oil mainly contributes non-pollutant local externalities such as congestion, accidents, and road damage. Table 2 compares the monetized value of fossil fuel subsidies and local externalities to regional consumption. Globally,

FIGURE 2. Global explicit and implicit fossil fuel subsidies by energy product and subsidy component

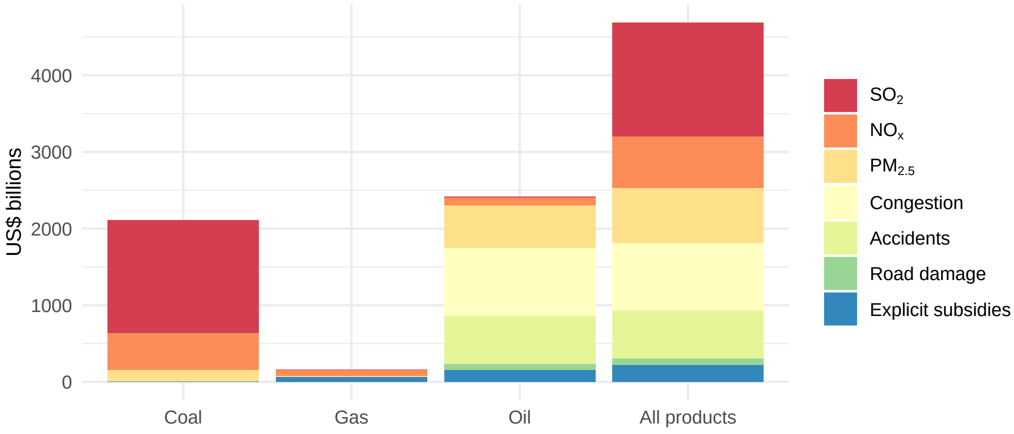


TABLE 2. Summary statistics on the magnitude of explicit fossil fuel subsidies and local externalities

Region	Consumption	Explicit fossil fuel subsidies		Combined local externalities	
	bill. $2017	bill. $2017	% of cons.	bill. $2017	% of cons.
ARG	466.0	2.4	0.5	13.2	2.8
AUS	811.9	—	—	26.1	3.2
BRA	1’411.3	—	—	38.4	2.7
CAN	1’056.4	—	—	47.3	4.5
CHN	5’733.7	18.1	0.3	1’842.7	32.1
DEU	2’045.0	—	—	86.9	4.2
FRA	1’530.2	—	—	58.7	3.8
GBR	1’950.0	—	—	52.8	2.7
IDN	615.2	13.3	2.2	35.5	5.8
IND	1’806.6	20.3	1.1	272.5	15.1
ITA	1’241.6	—	—	34.7	2.8
JPN	2’870.1	—	—	215.2	7.5
KOR	818.4	0.1	0.0	98.9	12.1
MEX	787.3	0.1	0.0	29.7	3.8
RCIS	339.6	13.6	4.0	62.6	18.4
REDA	1’303.8	4.3	0.3	81.7	6.3
REU	4’485.4	—	—	350.9	7.8
RLAC	1’400.4	13.4	1.0	71.8	5.1
RMEN	1’758.2	95.1	5.4	75.9	4.3
ROTW	926.1	0.3	0.0	60.3	6.5
RSSA	905.4	1.1	0.1	19.3	2.1
RUS	877.2	11.5	1.3	288.3	32.9
SAU	309.4	27.8	9.0	40.6	13.1
TUR	532.3	—	—	65.6	12.3
USA	14’190.9	—	—	472.1	3.3
ZAF	245.3	—	—	24.0	9.8
World	50’417.6	221.4	0.4	4’465.8	8.9

Notes: Own calculations based on data on explicit subsidies from the Global Trade Analysis Project (Aguiar et al., 2022) and on local externalities (Parry et al., 2014; Coady et al., 2017). “Combined local externalities” refers to the aggregate sum of externalities across different fossil fuels, sectors, and types of externalities for a given region.

local externalities exceed explicit subsidies by a factor of 20. Explicit subsidies represent only 0.4% of global consumption, while local externalities account for 8.9%. Regionally, local externalities typically outweigh explicit subsidies, with explicit subsidies being significant in only about 50% of regions.[12] They are most prevalent in Saudi Arabia, the Middle East & North Africa, the RCIS, and Indonesia reaching up to 9% of consumption. Local externalities are particularly high in China, Russia, and many other Asian and Middle Eastern countries.[13]

Regional disparities in local externalities from fossil energy use are substantial. To disentangle the drivers of regional heterogeneity, we apply the following decomposition:

$$\underbrace{\frac{D_r}{\overline{U}_r}}_{\substack{\text{Local externalities}\\\text{relative to consumption}}} \equiv \underbrace{\frac{D_r}{q_r^{\textit{Fossil energy used}}}}_{\substack{\text{Externality intensity}\\\text{of fossil energy use}\\[\$/mtoe]}} \times \underbrace{\frac{q_r^{\textit{Fossil energy used}}}{\overline{U}_r}}_{\substack{\text{Fossil energy intensity}\\\text{of consumption}\\[mtoe/\$]}} \tag{17}$$

where, in line with (1) and (2), $\overline{U}_r$ is consumption observed in the benchmark, $D_r = \sum_x D_{xr}$ are combined damages of local externalities, and $q_r^{\textit{Fossil energy used}} = \sum_{f,g} q_{fgr}^{\textit{Fossil energy used}}$ is the amount of fossil fuels used (in physical units of energy). A similar calculation yields the decomposition by type of fossil fuel.

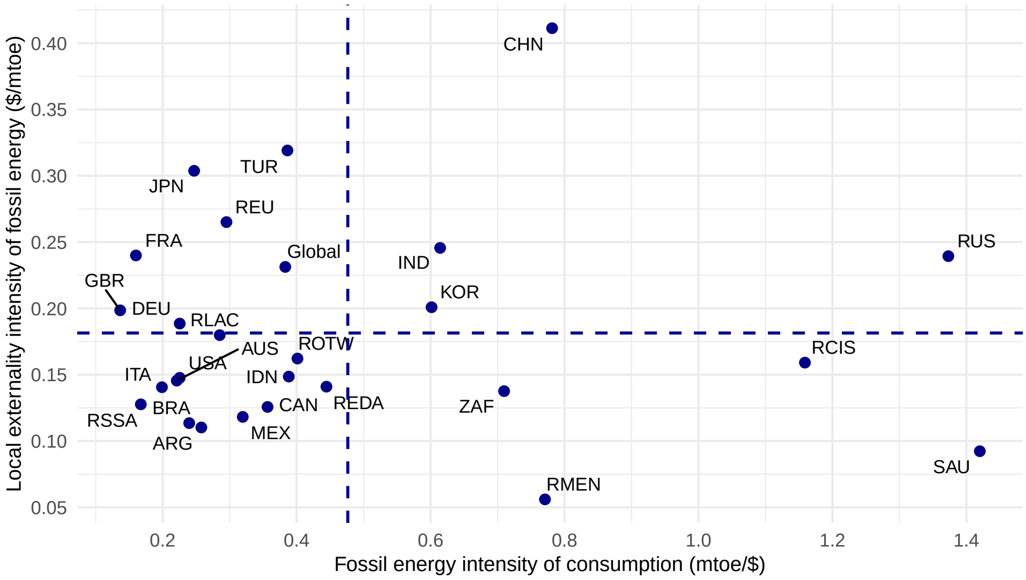
Figure 3 displays the results of the decomposition. Panel (a) shows a considerable regional variation in the intensity of local externalities in relation to a physical unit of energy (aggregated across all fossil fuel types), along with differing energy intensities of regional economic activity. The decomposition points to different underlying causes for the prevalence of local externalities in relation to consumption. For example, for Russia the large prevalence of local damages is more strongly driven by high energy intensity of consumption, while for China it is more due to the high damage per unit of fossil energy used. Large externalities for regions in the lower right corner (for example, Saudia Arabia and RCIS) are due to relatively high fossil use other than externality intensity, and vice versa for regions in the upper left corner (for example, Japan, France, and Turkey). Countries such as the United States, India and Germany are closer to the respective global average in both dimensions.

Panel (b) further decomposes both intensities by fossil fuel type. Regional heterogeneity in terms of the intensity of local externalities of fossil energy use is smallest for natural gas, while there exists considerable between-country variation for coal and oil. For example, China has a particularly high level of damage due to local externalities per unit of coal used, while the damage per unit of oil is much closer to the global average. By contrast, Japan has a high intensity associated with oil use and a relatively low intensity associated with coal. This suggests that

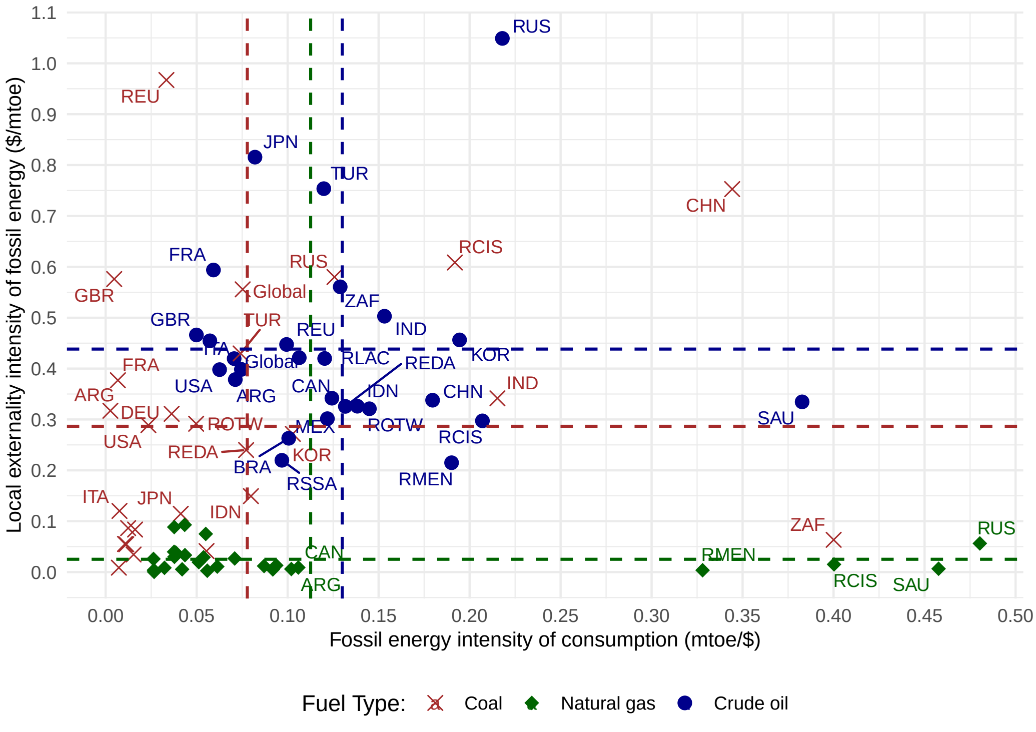
[12]Based on Table 2, Figure 1 visualizes the size of explicit and implicit subsidies relative to consumption for selected countries and regions on a global map.

[13]Table C.3 in the Online Appendix provides further detail on the size of fossil fuel subsidies and local externalities by region and by type of fossil fuel.

Figure 3. Decomposition of the size of local externalities related to fossil fuel use by region



(a) Aggregated over all fossil fuels



(b) By type of fossil fuel

Notes: Own calculations based on data from Global Trade Analysis Project (Aguiar et al., 2022), version 11, and Parry et al. (2014); Coady et al. (2017). The decomposition is based on the formula in (17), which identifies the externality intensity of fossil energy use (shown on the y-axis) and the fossil energy intensity of consumption (shown on the x-axis). Panel (a) shows the decomposition aggregated over all fossil fuels. Panel (b) provides a further disaggregation by type of fossil fuel. *mtoe*=million tons of oil equivalents. Dashed lines represent the average of the respective axis across regions.

Table 3. Design of counterfactual experiments

Dimension	Specifications	Scenario name
Fossil fuel subsidy removal		
Explicit subsidies		
	Fossil fuel subsidies	Subsidy removal
Implicit subsidies (Local externality pricing)		
	Local air pollutants	LPOLL
	Non-pollutant externalities	NPOLL
	LPOLL and NPOLL	Full
Geographic scope of implementation		
	Unilateral, i.e. one region at a time	Unilateral
	All regions jointly	Global
International trade closure		
	Small open economy	SOE
	Multi-regional trade	MRT
Climate mitigation policy		
	CO_2 emissions reductions according to NDCs under Paris agreement and compatible with 2°C warming	Paris2C

the regional variation in the externality intensity of aggregated fossil energy use is largely driven by the between-country differences for the same fossil fuel.

IV. Preliminaries

In this section, we first outline the design of our counterfactual experiments, which are used to assess the welfare effects of removing fossil fuel subsidies and implementing local Pigouvian energy pricing. We then present evidence demonstrating that neglecting international market responses introduces significant bias in estimating both the welfare effects and CO_2 emission reductions associated with fossil fuel subsidy removal.

A. Design of Counterfactual Experiments

We examine the welfare implications of accurately reflecting local energy prices by eliminating both explicit subsidies (see Definition 1) and implicit subsidies on fossil fuels. The latter entails taxing local externalities associated with fossil energy consumption based on their marginal damage. The simultaneous removal of explicit and implicit subsidies aligns with our concept of local Pigouvian pricing (see Definition 2).

Table 3 presents an overview of the dimensions and specifications of our counterfactual experiments. To assess the quantitative significance of different subsidy components, our analysis sequentially examines explicit subsidies, the pricing of local air pollutants, and local non-pollutant externalities. Additionally, we evaluate the welfare effects of a unilateral subsidy removal, wherein one country or region eliminates subsidies while all others maintain existing explicit subsidies and do not price local externalities. This approach provides insights into the unilateral incentives for subsidy reform across different countries and regions. Finally, we consider a scenario in which fossil fuel subsidies are globally eliminated, leading all countries and regions to adopt local Pigouvian energy pricing. While being highly hypothetical, it offers a valuable estimate of the welfare gains currently foregone in a globalized economy that remains deeply reliant on fossil energy.

Fossil fuels are deeply embedded in economic output and welfare through global supply chains for goods and services. To assess the role of international markets and economic interdependencies in evaluating local Pigouvian energy pricing, our counterfactual experiments incorporate variations in the international trade closure of our equilibrium model. In a small-open economy (SOE) setting, a country or region cannot pass on the costs of higher energy prices to international markets. Simultaneously, net fossil energy exporters may experience adverse effects if major trade partners reduce energy imports as a result of subsidy removal and the internalization of local externalities. We compare the SOE model to a multi-region trade (MRT) model which assumes bi-lateral Armington trade flows and endogenous international price effects.

Finally, we investigate the extent to which local Pigouvian energy pricing contributes to countries and regions meeting their climate policy ambitions. To provide a global perspective, we assess how aligning fossil energy prices with true costs affects both national welfare and the (shadow) carbon price required to achieve a country's 2°C-compatible NDC under the Paris Agreement.

B. The Bias from Not Incorporating International Market Effects

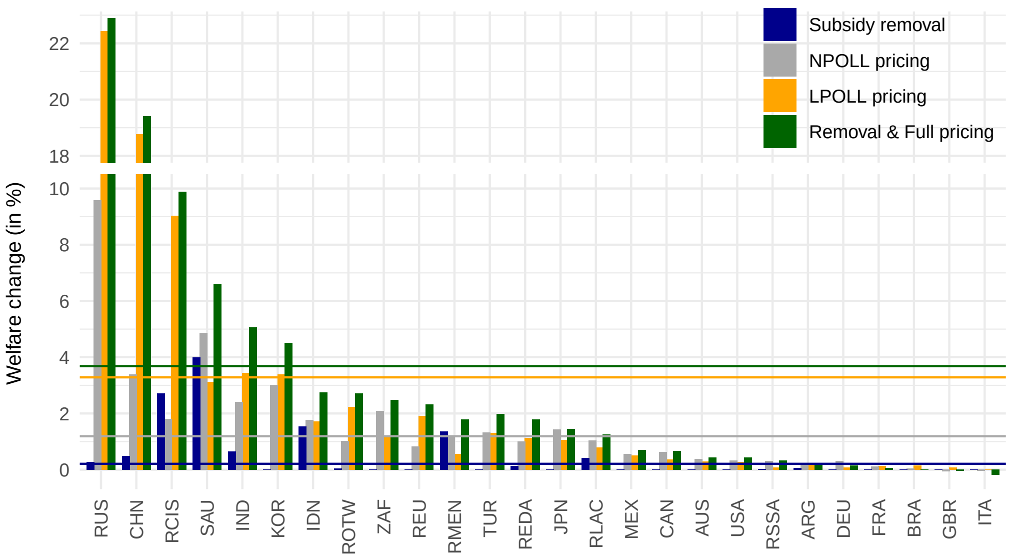
To assess the potential bias arising from disregarding the response of international markets and global supply chains, we compare estimates from the SOE model with those from the MRT model. Our findings indicate that the welfare effects estimated using the MRT model differ from those of the SOE model in both sign and magnitude, particularly at the country and regional levels.[14] This section summarizes our main insights. The Online Appendix provides additional detail to substantiate these findings.

The discrepancy between the MRT and the SOE models arises because the SOE framework omits several critical adjustment mechanisms that shape an economy's response to the removal of explicit and implicit fossil fuel subsidies. Under the SOE assumption, import and export prices remain fixed, preventing countries from passing forward the costs of higher domestic energy prices resulting from subsidy removal and local externality pricing. The limitations of the SOE framework become even more pronounced when countries or regions collectively eliminate fossil fuel subsidies. The removal of these subsidies reduces global demand for fossil energy, adversely impacting net energy-exporting countries.

Neglecting the responses of international markets and global supply chains also leads to biased estimates of CO_2 emissions reductions. Under the MRT–Global scenario, the removal of fossil fuel subsidies results in a 32% reduction in global

[14] At the same time, we find that when measuring global average impacts that the international market bias is less pronounced. This suggests that a global model without detailed country- or region-specific differentiation may still provide a reasonable first-order approximating of measuring the aggregate, global effects of fossil fuel subsidy removal.

FIGURE 4. Welfare effects of unilateral local pricing of externalities by region by scope of externality pricing



Notes: The percentage welfare change is measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy.

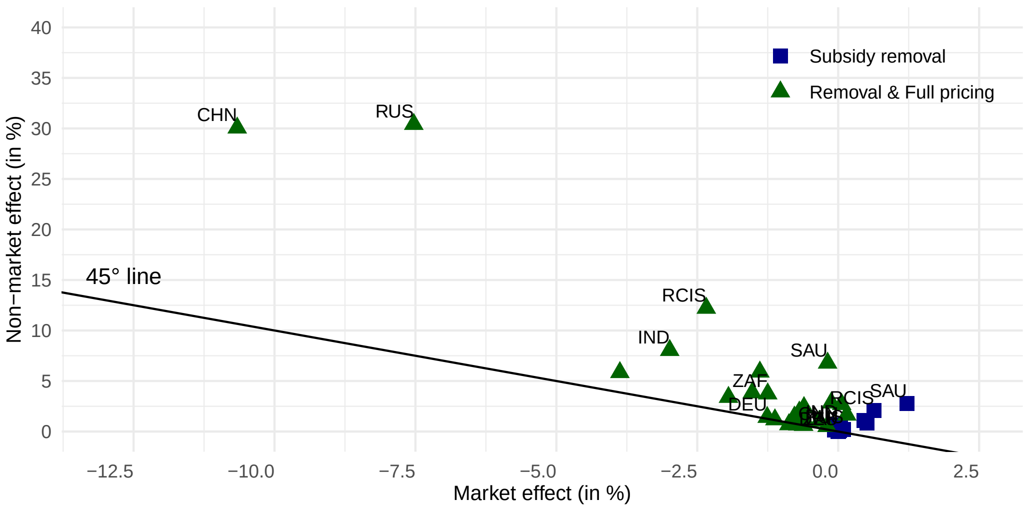
emissions, compared to a 37% reduction under the SOE model. In the SOE model, fossil energy-intensive products can shift towards imports when local energy pricing reforms are implemented, as regional policies do not affect international prices. In contrast, the MRT model assumes that global energy pricing reforms lead to higher fossil fuel prices and upstream product costs on international markets. This reduces the incentive to import from or shift production to other regions, resulting in consistently lower CO_2 emissions reductions both regionally and globally.

Given that the SOE framework overlooks key channels essential for evaluating the welfare effects of fossil fuel subsidy removal in a globalized economy with interconnected goods and energy markets, we base our main analysis on the MRT model.

V. Quantitative Results

In this section, we present and discuss our main findings. First, we analyze the unilateral incentives for countries when other countries do not adopt local Pigouvian energy pricing. Second, we assess the global and regional foregone welfare gains resulting from the continued unregulated use of fossil fuels in today's globalized economy. Finally, we quantify the potential benefits for climate change mitigation—aligned with the 2°C-compatible Paris Agreement targets—in a counterfactual world with local Pigouvian energy pricing implemented globally.

FIGURE 5. Decomposition of welfare effects from subsidy removal and full pricing of local externalities into market and non-market effects by region



Notes: Percentages changes in market and non-market welfare, following the definition of welfare in (1), are measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy. In Panel (b) the axis "Market effect (in %)" refers to the weighted %-change in market welfare ($\%\Delta U_r$). Axis "Non-market effect (in %)" refers to weighted %-change of the negative non-market effect ($-\%\Delta E_r$). Percentage changes are weighted by their benchmark share in total welfare ($\overline{U}_r/\overline{W}_r$ respectively $\overline{E}_r/\overline{W}_r$). Summing up the two effects yields the welfare change (in %) as depicted in Figure Panel (a).

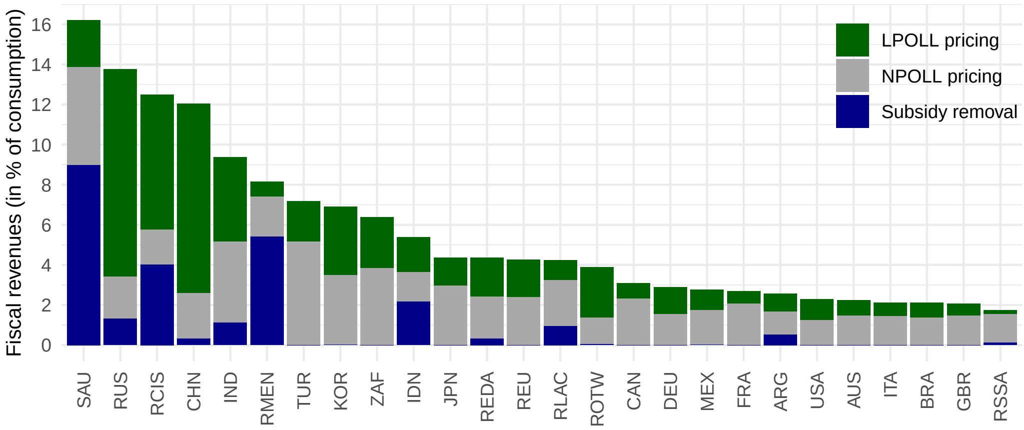
A. *Unilateral Pigouvian Energy Pricing*

We analyze a country's incentives for unilateral implementation from three distinct perspectives: (1) we assess the market and non-market welfare effects, (2) we quantify the fiscal revenues that could be generated by correctly pricing energy, and (3) we explore how local Pigouvian energy pricing affects the cost of achieving a country's climate targets under the Paris Agreement.

COMBINED WELFARE EFFECTS.—Figure 4 reports the welfare effects by country or region from the unilateral removal of both explicit and implicit fossil fuel subsidies, depending on the scope of pricing. Several key insights emerge. First, removing explicit fossil fuel subsidies results in modest welfare gains for most countries, with an average welfare gain of 0.2%. Given the relatively small magnitude of explicit fossil fuel subsidies in most industrialized countries, the associated welfare effects are also small. However, for several regions, welfare gains are notably larger, including Saudi Arabia (4.0%), Commonwealth countries (RCIS) (2.7%), Indonesia (1.5%), and countries in the Middle East and North Africa (RMEN) (1.4%).

Second, incorporating Pigouvian pricing of local externalities (i.e., removal and full pricing) results in substantial benefits, with an average welfare gain of 3.7%. Notably, implementing energy price reforms through a unilateral policy approach would lead to welfare improvements for almost every country or region. Coun-

FIGURE 6. Fiscal revenues per year (in % of consumption) of unilateral fossil fuel subsidy removal and Pigouvian pricing of local externalities



tries or regions with high fossil fuel use intensity or high energy intensity of consumption—such as China, India, Saudi Arabia, Russia, and the RCIS—would see significant welfare gains, ranging from 5% to 23%, due to the implementation of local Pigouvian energy pricing. These countries fall in the upper and lower right quadrants defined by the global averages in Figure 3.

Third, pricing only externalities related to local air pollution (LPOLL) captures most of the welfare benefits, yielding an average welfare gain of 3.3%. This approach accounts for 89% of the total welfare gains from full Pigouvian pricing. Notably, for countries like China and Russia, Pigouvian pricing of local air pollution externalities alone would result in substantial welfare gains of approximately 20%. Fourth, pricing non-pollutant local externalities increases welfare by an average of 1.3%. Despite being less impactful overall, it proves to be the most effective policy in several regions, including Saudi Arabia, South Africa, Canada, and Germany.

DECOMPOSING MARKET AND NON-MARKET WELFARE.—Figure 5 decomposes the welfare change of a country or region into market and non-market components, following the definition of W_r in equation (1). Several key insights emerge. First, removing explicit fossil fuel subsidies (where they exist) improves welfare on both dimensions. Market welfare increases as subsidy removal reduces market distortions, narrowing the gap between producer and consumer prices of energy. Additionally, the reduction in fossil energy use leads to positive non-market welfare effects. Second, when applying Pigouvian pricing of local externalities, market and non-market welfare do not move in the same direction, revealing a trade-off between the two. While Pigouvian pricing increases non-market welfare, higher energy prices lead to economic costs in terms of market-based consumption, resulting in a decrease in market welfare. Our findings show a positive net effect for nearly all countries, with most countries falling above the 45° line. Countries with high marginal damages or high energy intensity of consumption (or both) experience particularly large welfare gains.

FISCAL REVENUE EFFECTS.—Figure 6 shows the fiscal revenues, expressed as a percentage of consumption, that could be generated annually by local Pigouvian energy pricing. This includes both budgetary savings from eliminating explicit fossil fuel subsidies and tax revenues from pricing local externalities.

We find that fiscal revenues from a unilateral approach to correct local energy prices would be substantial. On average, countries or regions would generate revenues equal to 4.9% of consumption, or $223 billion per year (in 2017 USD), ranging from 1.8% to 16.2% at the country or regional level. Removing explicit subsidies would, on average, contribute only 0.4% (or $7 billion) to additional fiscal income annually, whereas pricing local externalities would generate significantly larger revenues. Pricing externalities related to local air pollution would, on average, yield fiscal revenues equal to 2.5% of consumption, or $124 billion per year, while pricing non-pollutant externalities would generate 2.0% of consumption, or $91 billion per year.[15]

Looking more closely at European countries, France, Germany, the United Kingdom, and other European nations could expect substantial public budget inflows, averaging 3.2% of consumption (or $103 billion), with total revenues reaching $359 billion per year (in 2017 USD), comprising $216 billion from pollutant externality pricing and $142 billion from non-pollutant externality pricing.

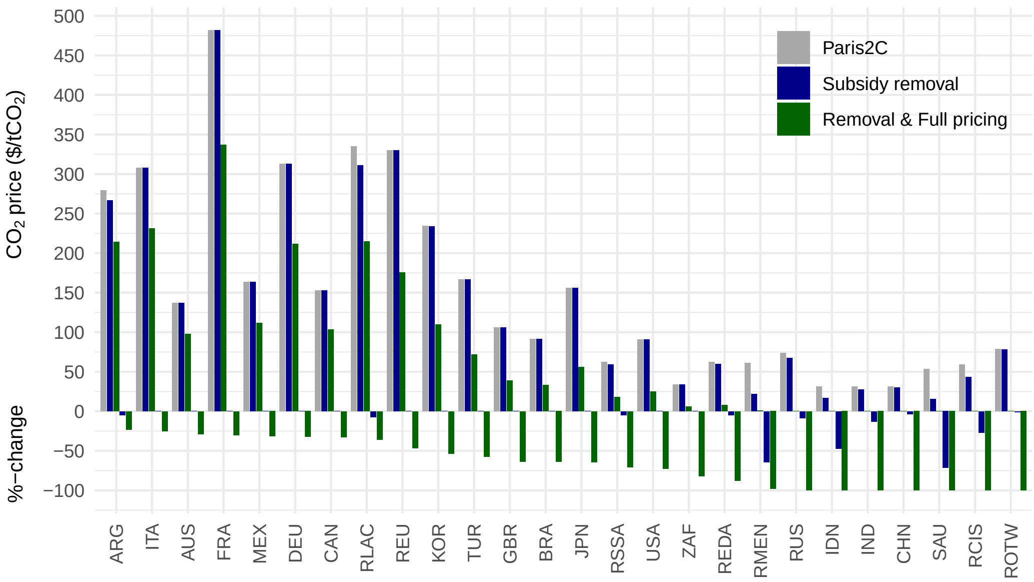
Globally, summing across all countries and regions, we estimate that total fiscal revenues from local Pigouvian energy pricing would amount to 4.9% of global consumption, or $2.5 trillion per year (in 2017 USD).

IMPLICATIONS FOR THE ECONOMIC COSTS OF CLIMATE TARGETS.—The case for unilateral local Pigouvian energy pricing may be further strengthened if it reduces the need for additional, costly carbon abatement measures that a country must implement to meet its climate targets under the Paris Agreement. We investigate this climate-related aspect of incentives for local energy pricing reforms using the concept of emissions-constrained Pigouvian energy prices (see Definition 3). Specifically, we ask how large is the reduction in the equilibrium (shadow) carbon price required to meet a country's 2°C-compatible Paris climate target when local Pigouvian pricing is introduced.

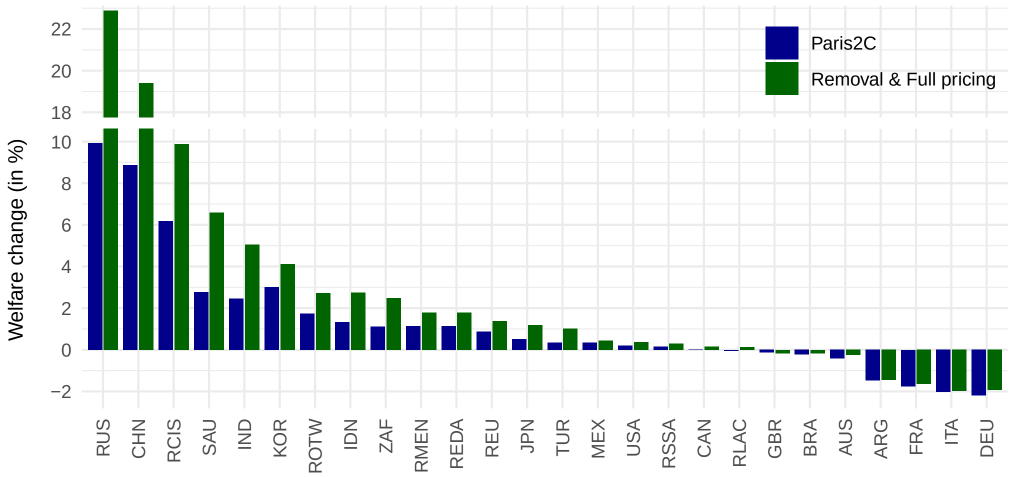
Figure 7, Panel (a), compares the carbon prices required to meet a country's or region's Paris climate target both without and with local Pigouvian energy pricing. First, explicit subsidy removal is applied in approximately 50% of regions, leading to an average reduction in carbon prices by 14% among this group of regions. Second, full pricing of local externalities results in a substantial decrease in the required carbon price, with an average reduction of 68%, equivalent to a drop in the average carbon price from $144 to $69 per ton of CO_2. Third, a striking result is that with local Pigouvian energy pricing, about one-third of countries and regions would already overachieve their NDC target, meaning the required carbon

[15]While pricing non-pollutant externalities has a relatively small impact on welfare (compared to pricing externalities from local air pollution), it plays a more significant role in fiscal revenue generation. This is largely because the demand for transportation services, and thus oil used for transportation, is relatively price inelastic. As a result, pricing non-pollutant externalities leads to minor changes in non-market welfare, while the limited quantity changes imply that the Pigouvian tax on transportation is applied to a relatively inelastic tax base.

FIGURE 7. Achieving Paris climate targets without and with unilateral local Pigouvian energy pricing



(a) Carbon prices or shadow cost of carbon



(b) Welfare (market and non-market) effects

Notes: "Paris2C" refers to achieving 2°C-compatible Paris targets with national carbon pricing only, i.e. without subsidy reform or additional pricing of local externalities. In panel (a), The y-axis shows the level of the CO_2 price π_r above and the respective percentage change below the zero line. Panel (b) shows the percentage welfare change relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy.

price to meet the Paris climate goal would be zero (a 100% reduction).

Figure 7, Panel (b), reports the welfare change, including both market and non-market effects, resulting from local Pigouvian energy pricing when combined with a climate policy based on the 2°C-compatible Paris targets. We find that achieving the climate target without removing explicit and implicit fossil fuel subsidies yields welfare gains for most countries and regions. On average, welfare increases by 1.5%.[16]

The key insight here is that most regions experience substantially higher welfare gains (or reduced welfare losses) if policies are designed to price local externalities related to fossil fuels in addition to achieving their climate targets. On average, across countries, adding Pigouvian energy pricing on top of carbon pricing to meet the Paris climate target increases welfare by 120% or 1.7 percentage points. The reason is that CO_2 pricing alone represents a cost-effective way to achieve the climate target, but does not take into account the non-market welfare cost created by the local externalities of fossil fuel consumption.

For countries that exceed their climate targets through Pigouvian energy pricing alone, additional climate policy is therefore redundant. For these countries, the carbon price falls to zero (see Figure 7, Panel (a)), suggesting that reducing fossil energy use through local Pigouvian pricing is more beneficial than relying only on climate policy measures. For countries that do not meet their climate target through Pigouvian energy pricing alone, the policy combination of Pigouvian energy pricing and carbon pricing enhances welfare compared to relying on carbon pricing alone.

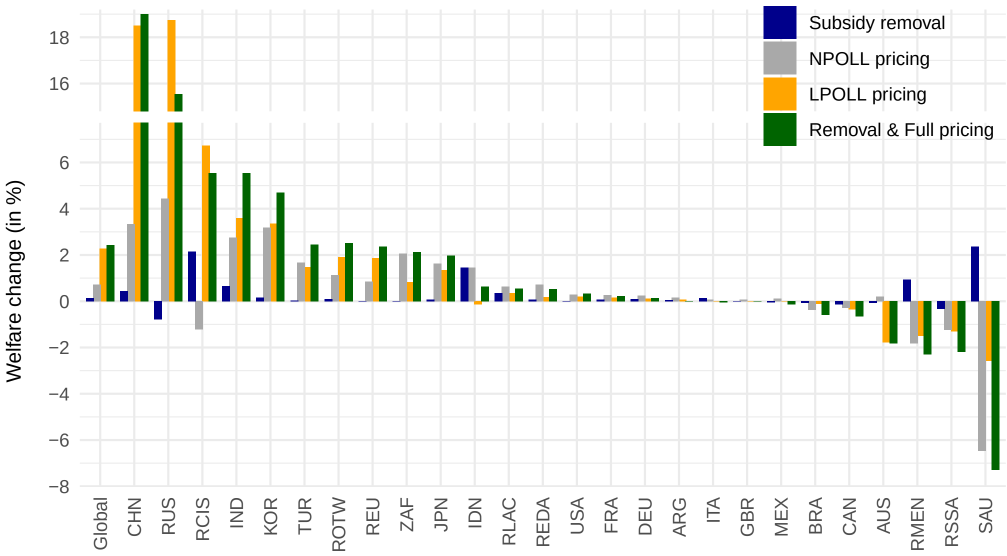
B. *Estimating the Foregone Welfare Gains from Fossil Fuel Use*

Economies worldwide remain heavily reliant on fossil fuels, the use of which entails substantial costs due to adverse local effects that are not internalized in market decisions. We next analyze a counterfactual world in which all countries and regions adopt local Pigouvian energy pricing. While such a multi-lateral pricing of local externalities represents arguably a hypothetical counterfactual, it provides a basis for quantifying the foregone global and regional welfare gains from the unregulated use of fossil fuels, i.e. from the mispricing of fossil fuels. Importantly, in deriving such estimates, it is crucial to take into account both the domestic and international market responses, as is featured by our model.

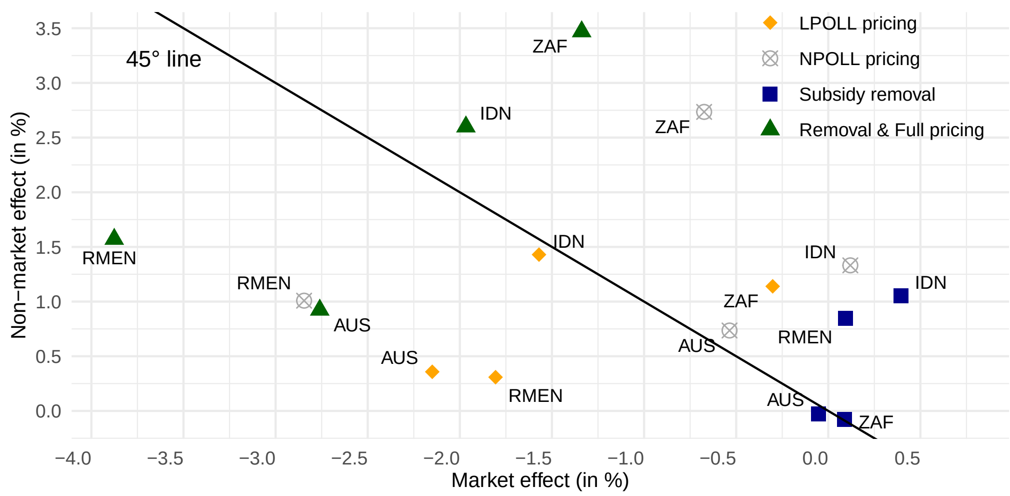
GLOBAL WELFARE EFFECTS.—Figure 8 presents the foregone welfare effects at both regional and global levels. Panel (a) illustrates the total welfare changes, while Panel (b) decomposes these into market and non-market welfare effects. Our estimates indicate that the welfare cost of unregulated fossil fuel use in the global economy amounts to 2.4% of global consumption (Panel (a)). Notably, implementing Pigouvian pricing for local air pollution externalities alone would capture over 90% of these welfare gains, resulting in a global welfare increase of 2.3%. Addi-

[16]That climate policy reducing GHG emissions can have considerable co-benefits is consistent with a large body of literature on the (local) co-benefits of climate change mitigation policies (see, for example, Nordhaus and Yang, 1996; Tol, 2002; Thompson et al., 2014; Li et al., 2018; Shindell et al., 2018; Tong et al., 2021; Huang et al., 2023).

Figure 8. Global and regional welfare effects of multi-lateral worldwide removal of fossil fuel subsidies and pricing of local externalities



(a) Welfare change by region



(b) Decomposition into market and non-market welfare change (for selected regions)

Notes: Percentages changes in (market and non-market) welfare, following the definition of welfare in (1), are measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy. In Panel (b), the axis "Market effect (in %)" refers to the weighted %-change in market welfare ($\%\Delta U_r$). Axis "Non-market effect (in %)" refers to weighted %-change of the negative non-market effect ($-\%\Delta E_r$). Percentage changes are weighted by their benchmark share in total welfare ($\overline{U}_r/\overline{W}_r$ respectively $\overline{E}_r/\overline{W}_r$). Summing up the two effects yields the welfare change (in %) as depicted in Panel (a).

tionally, pricing non-pollutant externalities would generate a 0.7% gain in global welfare. In contrast, the removal of explicit fossil fuel subsidies yields a relatively modest global welfare improvement of 0.1%.

WELFARE EFFECTS BY COUNTRY AND REGION.—Welfare gains (or losses) at the country or regional level are smaller (or larger) under global joint implementation compared to unilateral adoption of local Pigouvian energy pricing (see Figure 4). When all regions implement local Pigouvian pricing, the costs of fossil energy and energy-intensive imports rise. Unlike unilateral action, global adoption of local energy pricing limits firms' and consumers' ability to substitute imported goods in response to higher domestic energy and energy-intensive goods prices.

Fossil energy exporters experience welfare losses as global demand for fossil fuel imports declines. Panel (b) of Figure 8 illustrates these effects, with some regions falling below the 45° line—unlike the unilateral pricing case depicted in Figure 5, where all remain above it. For oil-exporting regions such as RCIS, RMEN, and Saudi Arabia, local energy pricing for oil-related transport use has the most significant welfare impact. However, these losses are mitigated or offset when subsidy removal and comprehensive pricing scenarios are considered, particularly for RCIS. Similarly, coal exporters such as Indonesia, Australia, and Canada experience welfare losses as coal demand declines with comprehensive pricing of local pollutants. In contrast, Russia and South Africa gain more from pricing their local pollutant externalities than they lose from reduced coal trade.

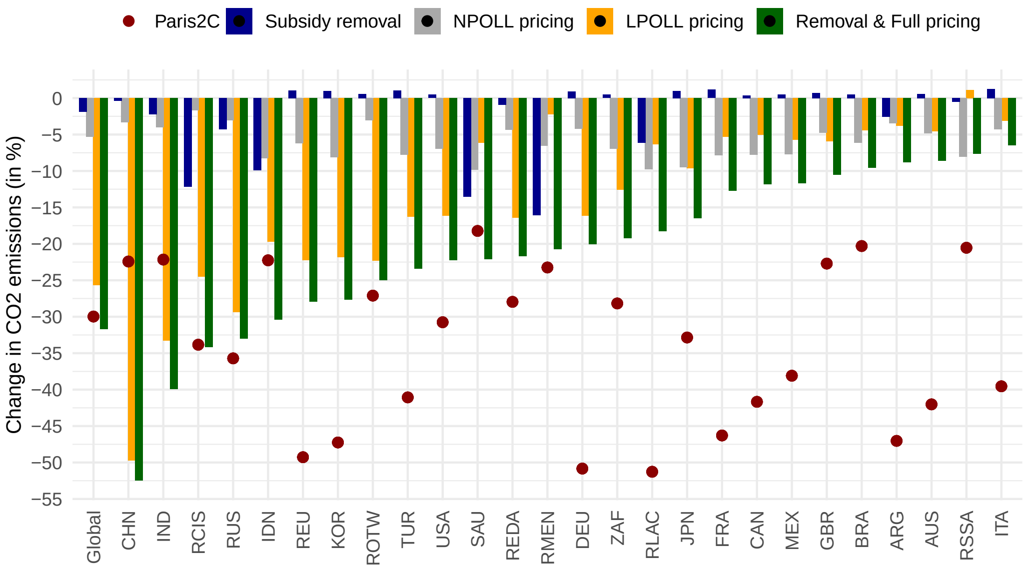
In summary, our analysis shows that local Pigouvian energy pricing is advantageous for all countries and regions, even for those facing welfare losses due to reduced fossil fuel export revenues—provided it is implemented globally.

C. Global Pigouvian Energy Pricing: Co-Benefits for Climate Mitigation

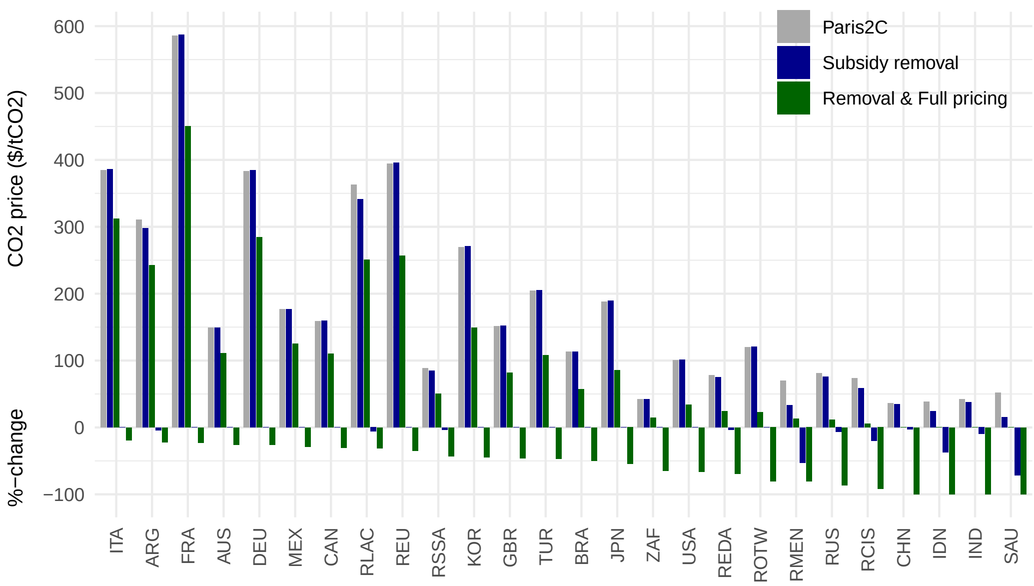
We finally examine the climate change mitigation benefits of multi-lateral, local Pigouvian energy pricing if adopted by all countries and regions. While hypothetical, this counterfactual analysis helps evaluate the extent to which pricing fossil energy to internalize local externalities could contribute to global and national progress toward the Paris Agreement climate goals. The guiding questions are: To what extent would global carbon emissions decline under global Pigouvian pricing? How close would countries be to meeting their national climate targets? What are the implications for welfare costs and carbon prices required to achieve the 2°C-compatible Paris targets?

Figure 9, Panel (a), compares global and regional CO_2 emission reductions at varying levels of local Pigouvian energy pricing with the climate targets outlined in the Paris Agreement. We estimate that global emissions would decrease by 32% if all regions implemented comprehensive energy pricing reforms, including the removal of subsidies and full pricing of local externalities. At the global level, this reduction would already meet the required emissions cut consistent with a 2°C development pathway under the Paris Agreement. A substantial portion of this reduction (i.e., a 26% reduction in emissions) is attributable to the pricing of local externalities related to air pollution. In contrast, the global removal of fossil fuel subsidies would contribute only marginally to meeting the Paris targets, yielding

FIGURE 9. Achieving Paris climate targets without and with global local Pigouvian energy pricing



(a) CO_2 emissions reductions



(b) Carbon prices or shadow cost of carbon

Notes: "Paris2C" refers to achieving 2°C-compatible Paris targets with national carbon pricing only, i.e. without subsidy reform or additional pricing of local externalities. In Panel (a), the percentages changes in emissions is measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy. In Panel (b), the y-axis displays the CO_2 price level, π_r, above the zero line, with the corresponding percentage change shown below it. The percentage change in the CO_2 price is measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes climate policy according to "Paris2C".

a mere 2% reduction in CO_2 emissions.[17] Additionally, internalizing non-pollutant externalities associated with oil use, primarily in transportation, would result in a 5% reduction in global CO_2 emissions.

There are significant regional disparities in the potential for achieving national 2°C-compatible Paris targets through local Pigouvian energy pricing. Approximately 20% of countries or regions, including major emitters like China, India, and Indonesia, would already meet their Paris targets. For most of these nations, pricing local air pollution externalities plays a key role in significantly reducing CO_2 emissions. However, for countries with substantial fossil energy subsidies, such as Saudi Arabia and other MENA countries, subsidy removal is crucial to achieving Paris targets through energy pricing reform. Additionally, other industrialized and energy-importing nations, including Germany, the United States, Japan, and the United Kingdom, would already meet over 30% of their Paris targets through local Pigouvian energy pricing.

Figure 9, Panel (b), reports changes in the shadow cost of carbon, as measured by a national carbon price, of meeting a country's or region's 2°C-compatible Paris target resulting from local Pigouvian energy pricing. On average across countries, the carbon price to achieve Paris targets is reduced by 60% and drops by more than 80% for about one third of countries. Importantly, the latter group of countries includes with China, the United States, and India the top three CO_2 emitters, which collectively account for over 53% of global emissions. Not surprisingly, removing explicit subsidies has only negligible effects on carbon prices for most countries, the exception being countries with high explicit subsidies on fossil fuels (such as Saudia Arabia and RMEN).

VI. Conclusion

The global public good nature of climate change mitigation and the associated free-rider problem require restructuring incentives for countries to price fossil energy consumption. This paper has examined the regional and global efficiency, distributional, and fiscal impacts of eliminating explicit and implicit fossil fuel subsidies. We develop a multi-region, multi-sector equilibrium model that incorporates data on fossil fuel subsidies, local external costs, and international market responses, capturing global supply chain dynamics and sector-specific details. Our findings show that while unilateral removal of explicit fossil fuel subsidies provides modest welfare and fiscal benefits, comprehensive local Pigouvian pricing, which also internalizes local externalities from fossil energy consumption, yields much greater gains. The integration of carbon pricing with local Pigouvian energy pricing lowers the cost of achieving climate goals for nearly all countries and regions. For countries that exceed their climate targets through Pigouvian energy pricing alone, additional climate policy is therefore superfluous. Removing explicit and implicit fossil fuel subsidies globally would reduce global CO_2 emissions by roughly one third while increasing global welfare. Our findings suggest that Pigouvian

[17]This estimate aligns with comparable studies, which find reductions in the range of 1–4% (Jewell et al., 2018; Chepeliev and van der Mensbrugghe, 2020; Arzaghi and Squalli, 2023).

pricing of fossil energy can align economic, fiscal, and climate objectives at both national and global levels.

Several limitations of our analysis point to valuable directions for future research. First, our estimates of welfare gains from Pigouvian energy pricing should be interpreted as a lower bound. On the one hand, we assume that the fiscal revenues are returned lump-sum foregoing additional gains from efficiency-enhancing use, for example, by reducing distortionary income taxes. On the other hand, we do not account for the potential positive effects of reduced air pollution on health and labor productivity. Second, the IMF data is the only available source providing comprehensive spatial and sectoral coverage of local marginal external costs associated with fossil energy use. However, this comes with the trade-off of lacking information on potential non-linearities and measurement uncertainty. As a result, our quantitative estimates rely on point estimates of constant marginal external costs. If the relationship between marginal external costs and fossil fuel consumption is positive and non-linear, we may somewhat overestimate the non-market welfare gains from reducing fossil fuel use through Pigouvian energy pricing. Third, while the economic rationale for Pigouvian energy pricing is strong, it has not gained widespread traction as a public policy—likely due to several challenges commonly associated with environmental taxation. These include higher energy prices, concerns about with-in country distributional effects and international competitiveness, and the influence of vested interests (Metcalf, 2009; Victor, 2009; Rausch, Metcalf and Reilly, 2011; Stiglitz, Stern et al., 2017; Baranzini et al., 2017). An important direction for future research therefore lies in better understanding the political economy dynamics and distributional consequences of removing explicit fossil fuel subsidies and pricing local externalities related to fossil energy use.

REFERENCES

Aguiar, Angel, Maksym Chepeliev, Erwin Corong, and Dominique van der Mensbrugghe. 2022. "The Global Trade Analysis Project (GTAP) Data Base: Version 11." *Journal of Global Economic Analysis*, 7(2).

Anenberg, Susan C., Joel Schwartz, Drew Shindell, Markus Amann, Greg Faluvegi, Zbigniew Klimont, Greet Janssens-Maenhout, Luca Pozzoli, Rita Van Dingenen, Elisabetta Vignati, Lisa Emberson, Nicholas Z. Muller, J. Jason West, Martin Williams, Volodymyr Demkine, W. Kevin Hicks, Johan Kuylenstierna, Frank Raes, and Veerabhadran Ramanathan. 2012. "Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls." *Environmental Health Perspectives*, 120(6): 831–839.

Armington, Paul. 1969. "A Theory of Demand for Products Distinguished by Place of Production." *International Monetary Fund Staff Papers*, 16: 159–76.

Arzaghi, Mohammad, and Jay Squalli. 2023. "The Environmental Impact of Fossil Fuel Subsidy Policies." *Energy Economics*, 126: 106980.

Baranzini, Andrea, Carlo Carraro, Yannis Katsoulacos, and Anil Markandya. 2017. "Carbon pricing in climate policy: Seven reasons, complementary instruments, and political economy considerations." *Wiley Interdisciplinary Reviews: Climate Change*, 8(4): e462.

Barrage, Lint. 2020. "Optimal Dynamic Carbon Taxes in a Climate–Economy Model with Distortionary Fiscal Policy." *The Review of Economic Studies*, 87(1): 1–39.

Barrett, Scott. 1994. "Self-Enforcing International Environmental Agreements." *Oxford Economic Papers*, 46: 878–94.

Barrett, Scott. 2003. *Environment and Statecraft: The Strategy of Environmental Treaty-Making.* Oxford University Press.

Barrett, Scott, and Robert Stavins. 2003. "Increasing Participation and Compliance in International Climate Change Agreements." *International Environmental Agreements: Politics, Law and Economics*, 3: 349–376.

Basaglia, Piero, Jonas Grunau, and Moritz A. Drupp. 2024. "The European Union Emissions Trading System Might Yield Large Co-Benefits from Pollution Reduction." *Proceedings of the National Academy of Sciences*, 121(28): e2319908121.

Baumol, William J., and Wallace E. Oates. 1988. *The Theory of Environmental Policy.* . 2nd ed., Englewood Cliffs, NJ:Prentice Hall.

Bilal, Adrien, and Diego R. Känzig. 2025. "Does Unilateral Decarbonization Pay For Itself?" NBER Working Paper 33364.

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

Böhringer, Christoph, Jared C. Carbone, and Thomas F. Rutherford. 2016. "The Strategic Value of Carbon Tariffs." *American Economic Journal: Economic Policy*, 8(1): 1–25.

Breton, Michèle, and Hossein Mirzapour. 2016. "Welfare Implication of Reforming Energy Consumption Subsidies." *Energy Policy*, 98: 232–240.

Bretschger, Lucas, and Evgenij Komarov. 2024. "All Inclusive Climate Policy in a Growing Economy: The Role of Human Health." *Environmental and Resource Economics*, 87(12): 3205–3234.

Brunel, Claire, and Erik Paul Johnson. 2019. "Two Birds, One Stone? Local Pollution Regulation and Greenhouse Gas Emissions." *Energy Economics*, 78: 1–12.

Caplan, Arthur J., and Emilson C. D. Silva. 2005. "An Efficient Mechanism to Control Correlated Externalities: Redistributive Transfers and the Coexistence of Regional and Global Pollution Permit Markets." *Journal of Environmental Economics and Management*, 49(1): 68–82.

Chen, Henry, Sergey Paltsev, John M. Reilly, Jennifer F. Morris, and Mustafa H. Babiker. 2015. "The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption." MIT Joint Program Report Series, March 2015.

Chepeliev, Maksym, and Dominique van der Mensbrugghe. 2020. "Global Fossil-Fuel Subsidy Reform and Paris Agreement." *Energy Economics*, 85: 104598.

Chepeliev, Maksym, Robert McDougall, and Dominique van der Mensbrugghe. 2018. "Including Fossil-Fuel Consumption Subsidies in the GTAP Data Base." *Journal of Global Economic Analysis*, 3(1): 84–121.

Clements, Benedict, David Coady, Stefania Fabrizio, Sanjeev Gupta, and Baoping Shang. 2014. "Energy Subsidies: How Large Are They and How Can They Be Reformed?" *Economics of Energy & Environmental Policy*, 3(1).

Coady, David, Ian Parry, Louis Sears, and Baoping Shang. 2017. "How Large Are Global Fossil Fuel Subsidies?" *World Development*, 91(Supplement C): 11–27.

Coady, David, Ian Parry, Nghia-Piotr Le, and Baoping Shang. 2019. "Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates IMF Working Paper Fiscal Affairs Department Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates Prepared By." International Monetary Fund 89.

Coase, Ronald H. 1960. "The Problem of Social Cost." *Journal of Law and Economics*, 3: 1–44.

Davis, Lucas W. 2014. "The Economic Cost of Global Fuel Subsidies." *American Economic Review*, 104(5): 581–585.

Droste, Nils, Benjamin Chatterton, and Jakob Skovgaard. 2024. "A Political Economy Theory of Fossil Fuel Subsidy Reforms in OECD Countries." *Nature Communications*, 15(1): 5452.

Fullerton, Don, and Daniel H. Karney. 2018. "Multiple Pollutants, Co-Benefits, and Suboptimal Environmental Policies." *Journal of Environmental Economics and Management*, 87: 52–71.

Goulder, Lawrence H., Ian W. H. Parry, Roberton C. Williams III, and Dallas Burtraw. 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics*, 72(3): 329–360.

Harrison, Glenn W., Thomas F. Rutherford, and David G. Tarr. 1997. "Quantifying the Uruguay Round." *Economic Journal*, 107: 1405–1430.

Huang, Xinyuan, Vivek Srikrishnan, Jonathan Lamontagne, Klaus Keller, and Wei Peng. 2023. "Effects of Global Climate Mitigation on Regional Air Quality and Health." *Nature Sustainability*, 6(9): 1054–1066.

Inchauste, Gabriela, and David G. Victor. 2017. *The Political Economy of Energy Subsidy Reform.* Washington, DC: World Bank.

Intergovernmental Panel on Climate Change (IPCC). 2022. "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development." In *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.* 93–174. Cambridge:Cambridge University Press.

International Energy Agency. 2017. *World Energy Outlook 2017.*

Jarvis, Stephen, Olivier Deschenes, and Akshaya Jha. 2022. "The Private and External Costs of Germany's Nuclear Phase-Out." *Journal of the European Economic Association*, 20(3): 1311–1346.

Jewell, Jessica, David McCollum, Johannes Emmerling, Christoph Bertram, David E.H.J. Gernaat, Volker Krey, Leonidas Paroussos, Loïc Berger, Kostas Fragkiadakis, Ilkka Keppo, Nawfal Saadi, Massimo Tavoni, Detlef Van Vuuren, Vadim Vinichenko, and Keywan Riahi. 2018. "Limited Emission Reductions from Fuel Subsidy Removal except in Energy-Exporting Regions." *Nature 2018 554:7691*, 554(7691): 229–233.

Keramidas, Kimon, Florian Fosse, RINCON Andrea Diaz, Paul Dowling, Rafael Garaffa, Jose Ordonez, Peter Russ, Burkhard Schade, Andreas Schmitz, RAMIREZ Antonio Soria, DER VORST Camille Van, and Matthias Weitzel. 2023. "Global Energy and Climate Outlook 2023." Publications Office of the European Union, Luxembourg (Luxembourg).

Knittel, Christopher R., Douglas L. Miller, and Nicholas J. Sanders. 2016. "Caution, Drivers! Children Present: Traffic, Pollution, and Infant Health." *The Review of Economics and Statistics*, 98(2): 350–366.

Li, Mengpin, Da Zhang, Can T Li, Kathleen M Mulvaney, Noelle E Selin, and Valerie J Karplus. 2018. "Air quality co-benefits of carbon pricing in China." *Nature Climate Change*, 8(5): 398–403.

Mahdavi, Paasha, Cesar B. Martinez-Alvarez, and Michael L. Ross. 2022. "Why Do Governments Tax or Subsidize Fossil Fuels?" *The Journal of Politics*, 84(4): 2123–2139.

Mathiesen, Lars. 1985. "Computation of economic equilibria by a sequence of linear complementarity problems." In *Economic Equilibrium: Model Formulation and Solution.* , ed. Alan S. Manne, 144–162. Berlin, Heidelberg:Springer Berlin Heidelberg.

Metcalf, Gilbert E. 2009. "Designing a Carbon Tax to Reduce US Greenhouse Gas Emissions." *Review of Environmental Economics and Policy*, 3(1): 63–83.

Moslener, Ulf, and Till Requate. 2007. "Optimal Abatement in Dynamic Multi-Pollutant Problems When Pollutants Can Be Complements or Substitutes." *Journal of Economic Dynamics and Control*, 31(7): 2293–2316.

Narayanan, G., A. Badri, and R. McDougall, ed. 2012. *Global Trade, Assistance, and Production: The GTAP 8 Data Base.* Center for Global Trade Analysis, Purdue University.

Nordhaus, William. 2019. "Climate Change: The Ultimate Challenge for Economics." *American Economic Review*, 109(6): 1991–2014.

Nordhaus, William D., and Zili Yang. 1996. "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies." *The American Economic Review*, 86(4): 741–765. ArticleType: research-article / Full publication date: Sep., 1996 / Copyright © 1996 American Economic Association.

Paltsev, Sergey, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, Jim McFarland, Mustafa Sarofim, Malcolm Asadoorian, and Mustafa. Babiker. 2005. "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4." MIT Joint Program Report Series, Report 125.

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*, 06(04): 1550019.

Parry, Ian, Dirk Heine, Eliza Lis, and Shanjun Li. 2014. *Getting Energy Prices Right: From Principles to Practice.*

Parry, Ian W. H., and Roberton C. Williams. 1999. "A Second-Best Evaluation of Eight Policy Instruments to Reduce Carbon Emissions." *Resource and Energy Economics*, 21(3): 347–373.

Parry, Ian W. H., Simon Black, and Nate Vernon. 2021. "Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies." *IMF Working Papers*, 2021(236).

Pigou, Arthur Cecil. 1920. *The Economics of Welfare.* London:Macmillan and Co.

Rausch, S., G. E. Metcalf, and J. M. Reilly. 2011. "Distributional impacts of carbon pricing: a general equilibrium approach with micro-data for households." *Energy Economics*, 33(1): S20–S33.

Rutherford, Thomas F. 1995. "Extension of GAMS for Complementarity Problems arising in Applied Economics." *Journal of Economic Dynamics and Control*, 19(8): 1299–1324.

Rutherford, Thomas F. 2002. "Lecture notes on constant elasticity functions." *November, www.gamsworld.org/mpsge/debreu/ces.pdf (accessed 21 October 2011).*

Schlenker, Wolfram, and W. Reed Walker. 2016. "Airports, Air Pollution, and Contemporaneous Health." *The Review of Economic Studies*, 83(2): 768–809.

Shindell, Drew, Greg Faluvegi, Karl Seltzer, and Cary Shindell. 2018. "Quantified, Localized Health Benefits of Accelerated Carbon Dioxide Emissions Reductions." *Nature Climate Change*, 8(4): 291–295.

Stiglitz, Joseph E., Nicholas Stern, et al. 2017. "Report of the High-Level Commission on Carbon Prices." World Bank.

Thompson, Tammy M., Sebastian Rausch, Rebecca K. Saari, and Noelle E. Selin. 2014. "A Systems Approach to Evaluating the Air Quality Co-Benefits of US Carbon Policies." *Nature Climate Change*, 4(10): 917–923.

Tol, Richard S. J. 2002. "Welfare Specifications and Optimal Control of Climate Change: An Application of FUND." *Energy Economics*, 24(4): 367–376.

Tong, Dan, Guannan Geng, Qiang Zhang, Jing Cheng, Xinying Qin, Chaopeng Hong, Kebin He, and Steven J. Davis. 2021. "Health Co-Benefits of Climate Change Mitigation Depend on Strategic Power Plant Retirements and Pollution Controls." *Nature Climate Change 2021 11:12*, 11(12): 1077–1083.

Vandyck, Toon, Kimon Keramidas, Alban Kitous, Joseph V. Spadaro, Rita Van Dingenen, Mike Holland, and Bert Saveyn. 2018. "Air Quality Co-Benefits for Human Health and Agriculture Counterbalance Costs to Meet Paris Agreement Pledges." *Nature Communications*, 9(1): 4939.

Victor, David G. 2009. "The Politics of Fossil-Fuel Subsidies." Global Subsidies Initiative (www.globalsubsidies.org). SSRN Paper: 10.2139/ssrn.1520984.

The Welfare Effects of Explicit and Implicit Subsidies on Fossil Fuels

Supplementary Appendix: For Online Publication

Tim Kalmey, Sebastian Rausch, Jan Schneider[a]

Contents:

[a]Kalmey (tim.kalmey@zew.de), ZEW Leibniz Centre for European Economic Research, Mannheim, Germany. Schneider (jan.schneider@uol.de): Department of Business Administration, Economics and Law, Carl von Ossietzky University Oldenburg, Germany. Rausch (sebastian.rausch@zew.de), ZEW Leibniz Centre for European Economic Research, Mannheim, Germany, Department of Economics, Heidelberg University, Germany, Centre for Energy Policy and Economics at ETH Zurich, Switzerland, and Joint Program on the Science and Policy of Global Change at Massachusetts Institute of Technology, Cambridge, USA. We thank Maksym Chepeliev and GTAP for providing us with updated estimates on fossil fuel subsidies. The authors gratefully acknowledge funding by the European Commission under the Horizon Europe project "WeLaR–Welfare systems and labour market policies for economic and social resilience in Europe" (grant no. 101061388). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Appendix A. Translation of Paris climate targets (NDCs) to model context

We translate Nationally Determined Contributions (NDCs) submitted by countries to the UNFCCC into effective, 2°C-compatible reduction targets for CO_2 from fuel combustion relative to our model base year of 2017. Table A.1 shows the input data and reductions targets which enter the model. Our approach comprises the following steps:

1. Input data and adjustments for own baseline
We start with the original information on NDC as communicated by countries under the Paris agreement (see under column '*NDC as communicated*' in Table A.1). These include lower and upper bound %-reduction targets ('*NDC*', '*NDC+*'), base year ('t^{base}') and target year ('t^{target}'), the 'Type' of target setting (i.e, reduction target ('redu'), intensity target ('int')), and the 'Scope' of GHG emissions covered (i.e, 'All' GHG emissions, 'CO2' emissions).

2. Translation of reduction targets against 2017 emissions
We translate the NDCs into effective reduction targets against 2017 CO_2 emissions (our model base year) (see under column '*Adjusted for 2017 model baseline*'). Column 'CO_2^{base}' reports the CO_2 emission level in t^{base} relative to the model base year ($CO_2^{2017} = 1$). The CO_2 emission level (relative to 2017) for the upper bound target NDC_+ is:

$$CO_2^{NDC+} = CO_2^{\text{base}} \cdot (1 - \frac{NDC_+}{100})\,, \tag{A.1}$$

and the NDC_+ relative to the model base year 2017 is computed by:

$$NDC_+^{2017} = 100 \times (1 - CO_2^{NDC+})\,. \tag{A.2}$$

3. Adjusting for CO_2
For countries that have stated their NDCs in terms of total GHG emissions, we adjust their reduction targets, NDC_+^{2017}, using a CO_2 correction factor derived from the EU Commission's JRC-POLES model, as presented in the *Global Energy and Climate Outlook 2023* (Keramidas et al., 2023). This adjustment accounts for differences between overall GHG reduction commitments and the specific reductions in CO_2 emissions from fuel combustion. The correction factor is calculated as follows:

$$Corr^{CO_2} = \frac{\Delta\%CO_2}{\Delta\%\text{GHG}} \tag{A.3}$$

where: $\Delta\%CO_2$ represents the percentage reduction in CO_2 emissions from fuel combustion, and $\Delta\%GHG$ represents the percentage reduction in total GHG emissions, both taken from the JRC "NDC" scenario relative to a business-as-usual (BaU) reference scenario for the NDC target year, t^{target}. For instance, if a country commits to reducing total GHG emissions by 20% but reduces CO_2 emissions from fuel combustion by only 10%, the correction factor would be 0.5.

To refine these correction factors, we set a minimum value of 0.05 if a country's computed correction factor is zero or negative. This reflects the assumption that at least 5% of the GHG reduction stated in the NDC stems from decreased fossil fuel combustion. To remain conservative in our approach, we do not scale reduction targets upward, meaning that the correction factor is capped at 1.

These adjustments ensure a consistent and realistic alignment between NDC commitments and the reductions in CO_2 emissions from fossil fuel use.

4. Adjustments for negative and intensity targets

Additional adjustments to the reduction targets ensure that (1) no region has a negative reduction target and (2) setting a minimum absolute reduction target for countries with a emissions intensity target.

No Negative Reduction Targets: We ensure that no region has a negative reduction target, meaning that, at a minimum, all regions maintain their 2017 emission levels in our scenarios. There are two possible approaches: setting negative reduction targets to zero either before or after aggregating into model regions. If set to zero only after aggregation, countries within a model region could pool their targets. While this approach may be reasonable for some aggregated regions, we assume that each country individually must have a minimum reduction target of zero.

Minimum Target for Intensity-Based Commitments: For countries with emissions intensity targets, we impose a minimum reduction target of 5%. The rationale is that the translation of intensity targets is highly sensitive to GDP and CO_2 baseline assumptions, sometimes resulting in zero reduction requirements under IEO baselines. We assume that countries with intensity-based targets implement at least moderate policies leading to effective carbon pricing, even if their original NDC intensity target had already been met in 2017.

The final reduction targets, after accounting for CO_2 adjustments, negative reduction targets, and intensity-based targets, are reported in column NDC_{+}^{final} of Table A.1.

5. Global emissions budget approach to define Paris targets consistent with 2°C temperature target

To derive country-specific targets consistent with a 2°C temperature goal, we apply a budget-based approach grounded in the declared Paris Agreement targets. Specifically, we scale up these targets to ensure a global CO_2 emissions reduction of 25% relative to 2010 levels (or 30% relative to 2017). This reduction aligns with the threshold necessary to "limit global warming to below 2°C with at least 66% probability" (Intergovernmental Panel on Climate Change , IPCC).

To achieve this, we adjust each region's target emissions level (under NDC_{+}^{final}) by applying a uniform scaling factor of 0.82, ensuring that the global emissions target is met. This approach guarantees that every region has a positive reduction target, even if its initially reported target was zero. The 2°C-correction factor is derived by dividing the global emission level compatible with the 2°C target by the

TABLE A.1. Translation of NDC Paris targets to model context.

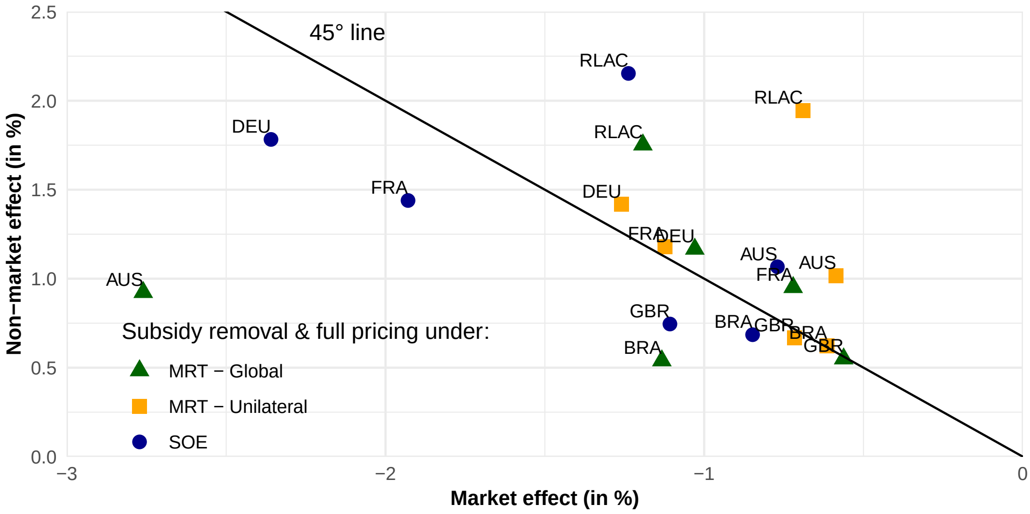
Country code	NDC as communicated by country under Paris agreement						Adjusted for 2017 model baseline			CO_2 and 2°C adjustment		
	Type	Scope	t^{base}	t^{target}	NDC	NDC_{+}	CO_2^{base}	$CO_2^{\text{NDC+}}$	NDC_{+}^{2017}	$Corr^{CO_2}$	NDC_{+}^{final}	NDC_{2C}^{final}
ARG	redu	All	2030	2030	15	30	0.90	0.63	37.2	0.95	35.4	47.0
AUS	redu	All	2005	2030	26	28	0.93	0.67	32.7	0.89	29.2	42.0
BRA	redu	All	2005	2025	37	37	0.72	0.45	54.7	0.05	2.7	20.3
CAN	redu	All	2005	2030	30	30	0.96	0.67	33.1	0.87	28.8	41.7
CHN	int	CO2	2005	2030	60	65	0.59	1.06	-5.7	1.00	5.0	22.2
DEU	redu	All	1990	2030	40	40	1.00	0.60	40.0	1.00	40.0	50.8
FRA	redu	All	1990	2030	40	40	1.09	0.66	34.5	1.00	34.5	46.3
GBR	redu	All	1990	2030	40	40	1.46	0.88	12.5	0.45	5.7	22.7
IDN	redu	All	2030	2030	29	41	1.38	0.81	18.6	0.28	5.1	22.3
IND	int	All	2005	2030	33	35	0.50	1.24	-23.6	0.05	5.0	22.2
ITA	redu	All	1990	2030	40	40	1.23	0.74	26.2	1.00	26.2	39.5
JPN	redu	All	2013	2030	26	26	1.09	0.81	19.0	0.95	18.0	32.8
KOR	redu	All	2030	2030	37	37	1.02	0.64	35.6	1.00	35.6	47.3
MEX	redu	All	2030	2030	22	36	0.94	0.60	40.0	0.61	24.4	38.1
RUS	redu	All	1990	2030	25	30	1.00	0.70	30.0	0.72	21.5	35.7
SAU	redu	All	2030	2030	0	0	1.00	1.00	0.2	0.91	0.2	18.2
TUR	redu	All	2030	2030	21	21	0.89	0.71	29.4	0.95	28.1	41.1
USA	redu	All	2005	2025	26	28	1.17	0.84	15.7	0.99	15.5	30.8
ZAF	redu	All	2010	2030	-33	14	1.01	0.87	12.7	0.97	12.3	28.2
RCIS	—	—	—	—	—	—	—	—	—	—	19.3	33.8
REDA	—	—	—	—	—	—	—	—	—	—	12.1	28.0
REU	—	—	—	—	—	—	—	—	—	—	38.1	49.3
RLAC	—	—	—	—	—	—	—	—	—	—	40.5	51.3
RMEN	—	—	—	—	—	—	—	—	—	—	6.3	23.2
ROTW	—	—	—	—	—	—	—	—	—	—	11.0	27.1
RSSA	—	—	—	—	—	—	—	—	—	—	3.0	20.5
Global	—	—	—	—	—	—	—	—	—	—	14.5	30.0

Notes: NDC as communicated: NDCs as communicated by the countries. *Type* {redu="CO_2 or GHG reduction target against a specific base year (possibly in the future)", int="CO_2 or GHG intensity target against a specific base year"}. *Scope* {All = "All GHG emissions", CO2 = "Target on CO_2 emissions only"}. t^{base}: Base year of NDC (year the NDC target is stated against). t^{target}: Target year of NDC (year the NDC is to be fulfilled). NDC: %-reduction based on lower Paris target. NDC_{+}: %-reduction based on upper Paris target.

Adjusted for 2017 model baseline: Translation of NDCs relative to our model base year of 2017. CO_2^{base}: CO_2 emission level in t^{base} relative to the model base year ($CO_2^{2017} = 1$). $CO_2^{\text{NDC+}}$: CO_2 emission level (relative to 2017) for NDC_{+}. NDC_{+}^{2017}: NDC_{+} (%) relative to the model base year 2017.

CO_2 and 2°C adjustment: Adjusting NDCs for other non-CO_2 emissions and scaling for 2°C-compatible development of global warming. $Corr^{CO_2}$: Applied CO_2 correction factor to translate from GHG to CO_2 emissions from fuel combustion. NDC_{+}^{final}: Resulting NDC_{+} (%) after applying $Corr^{CO_2}$ and corrections for taking into account negative and intensity targets. NDC_{2C}^{final}: %-reduction targets based on the Paris NDCs after adjusting for consistency with a 2°C temperature target based on an emissions budget approach and for translating to a base-year of 2017. Note that NDCs for aggregate regions were computed only after main corrections had been applied.

Figure B.1. Decomposition of welfare effects from local energy pricing into market and non-market effects under alternative international trade closures



Notes: Percentages changes in (market and non-market) welfare, following the definition of welfare in (1), are measured relative to a benchmark that includes existing explicit fossil fuel subsidies, excludes Pigouvian pricing of local externalities, and assumes no climate policy. Axis "Market effect (in %)" refers to the weighted %-change in market welfare ($\%\Delta U_r$). Axis "Non-market effect (in %)" refers to weighted %-change of the negative non-market effect ($-\%\Delta E_r$). Percentage changes are weighted by their benchmark share in total welfare ($\overline{U}_r/\overline{W}_r$ respectively $\overline{E}_r/\overline{W}_r$). Summing up the two effects yields the welfare change (in %) as depicted in Table B.2.

global emissions level implied by the NDC_{+}^{final} commitments. The final adjusted targets used in our scenario analysis are reported in column NDC_{2C}^{final}.

Appendix B. Additional results for international market effects

This section provides additional detail on the main findings summarized in Section IV.B.

Figure B.1 compares SOE (blue points) to MRT–Unilateral (yellow squares). It shows that the MRT model predicts welfare improvements for all countries following subsidy removal and full externality pricing. Notably, total welfare gains—including both market and non-market effects—are positive, as all countries lie above the 45° line. In contrast, the SOE model projects smaller welfare gains or even welfare losses for some countries. The ability to pass forward costs in the MRT framework allows countries with negative welfare effects under the SOE model (such as Germany, France, and the United Kingdom) to mitigate their adverse market impacts more effectively than the reduction in positive non-market effects, ultimately improving their overall welfare outcomes.

Moreover, Figure B.1 makes the point that the limitations of the SOE framework become even more pronounced when countries or regions collectively eliminate fossil fuel subsidies. The removal of these subsidies reduces global demand

Table B.2. Welfare bias from failing to account for international markets and global supply chains

Region	Absolute welfare change (%)			Welfare bias			
	SOE	MRT–Unil	MRT–Global	SOE vs. MRT–Unil.		SOE vs. MRT–Global	
				Δ	Δ%	Δ	Δ%
ARG	0.1	0.2	-0.0	-0.1	28.5	0.1	1’969.8
AUS	0.3	0.4	-1.8	-0.1	31.3	2.1	116.2
BRA	-0.2	0.0	-0.6	-0.2	1’790.0	0.4	72.6
CAN	0.5	0.7	-0.6	-0.2	31.9	1.1	170.2
CHN	18.9	19.4	19.0	-0.5	2.4	-0.1	0.4
DEU	-0.6	0.2	0.1	-0.7	462.3	-0.7	519.0
FRA	-0.5	0.1	0.2	-0.6	945.3	-0.7	312.4
GBR	-0.4	-0.0	-0.0	-0.3	642.9	-0.3	2’987.9
IDN	2.5	2.8	0.6	-0.2	8.7	1.9	297.8
IND	4.7	5.0	5.5	-0.4	7.6	-0.9	15.6
ITA	-0.5	-0.2	-0.1	-0.3	183.3	-0.4	698.4
JPN	1.0	1.4	2.0	-0.4	30.9	-1.0	49.1
KOR	3.3	4.5	4.7	-1.2	26.1	-1.4	29.0
MEX	0.6	0.7	-0.1	-0.1	19.9	0.7	519.7
RCIS	9.1	9.9	5.5	-0.8	7.8	3.6	64.5
REDA	1.4	1.8	0.5	-0.4	19.9	0.9	174.2
REU	1.2	2.3	2.4	-1.1	48.3	-1.1	49.0
RLAC	0.9	1.3	0.6	-0.3	27.1	0.4	63.4
RMEN	2.0	1.8	-2.3	0.2	12.3	4.3	187.5
ROTW	2.0	2.7	2.5	-0.8	27.5	-0.5	21.3
RSSA	0.1	0.3	-2.2	-0.2	65.1	2.3	105.1
RUS	22.6	22.9	15.6	-0.3	1.4	7.0	45.1
SAU	6.6	6.6	-7.3	-0.0	0.1	13.9	190.2
TUR	1.1	2.0	2.4	-0.9	45.7	-1.4	56.0
USA	0.2	0.4	0.3	-0.2	55.9	-0.1	43.2
ZAF	2.0	2.5	2.1	-0.5	20.1	-0.1	6.6
Global	2.6	—	2.4	—	—	0.2	7.2

Notes: “Absolute welfare change (%)” is relative to benchmark of no energy pricing reform. “SOE vs. MRT-Unil” and “SOE vs. MRT-Global” evaluate the change in welfare from a model with SOE trade closure to a model MRT trade closure for the case of “Unilateral” and “Global” implementation, respectively. Δ refers to the percentage point difference. Δ% refers to the “diff-in-diff”, i.e. the percentage change between the absolute welfare changes.

for fossil energy, adversely impacting net energy-exporting countries. Comparing SOE (blue points) to MRT–Global (green triangles) reveals that energy-exporting countries, such as Australia and Brazil, experience greater welfare losses in terms of market effects. On average, we find that the SOE model produces biased welfare estimates, with deviations of 60% (102%) compared to the MRT model under unilateral (global) fossil fuel subsidy removal. At the country and regional levels, these welfare biases are substantial, reaching up to 165% (253%) in the case of unilateral (global) implementation.

Table B.2 provides a detailed breakdown of welfare changes by region when comparing the SOE and MRT models, along with the calculated biases in welfare estimates.

Appendix C. Additional figures and tables

FIGURE C.2. Nested CES structure of domestic production for sectoral good Y_{gr}

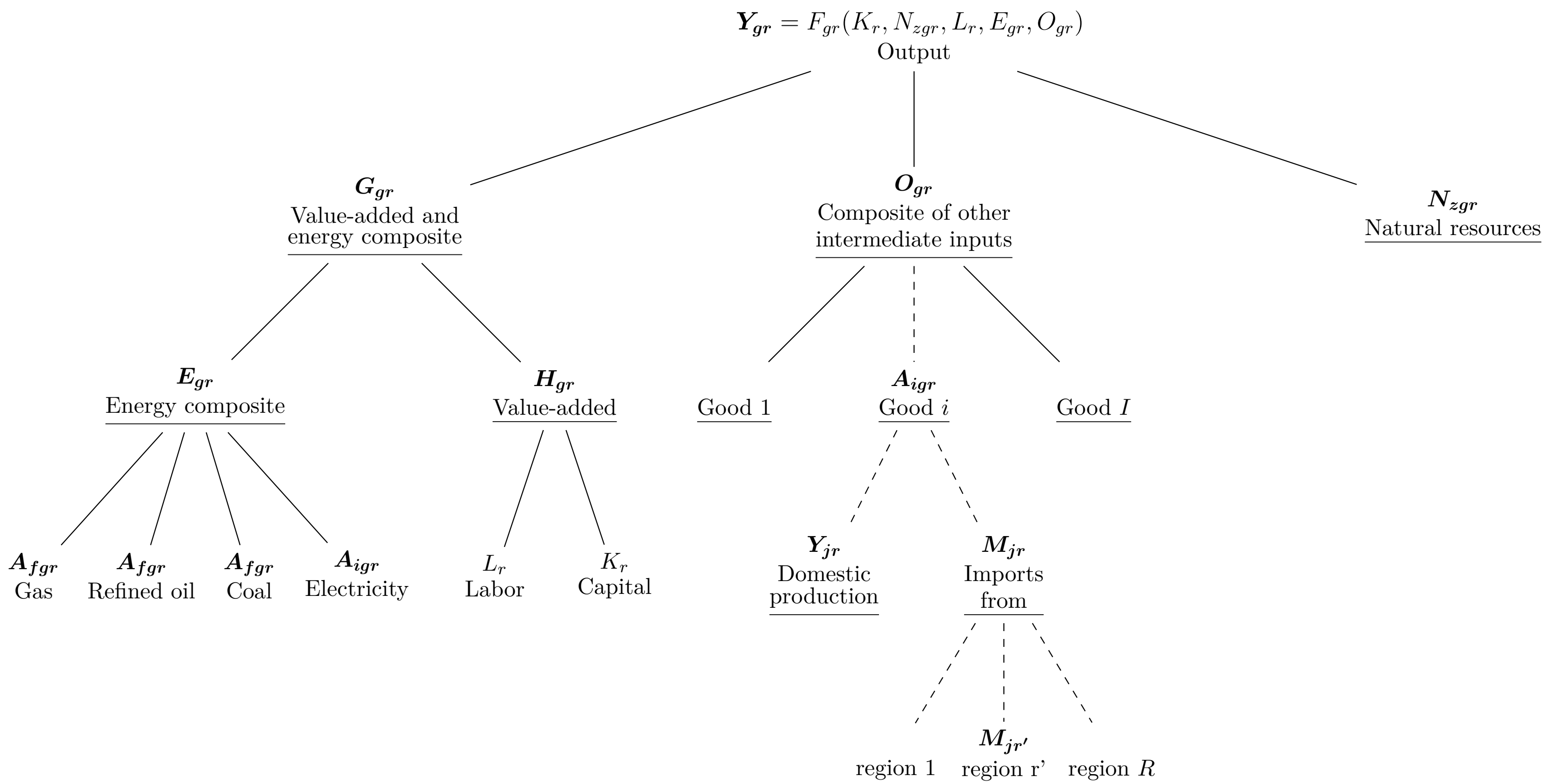


Table C.3. Descriptive statistics on fossil fuel subsidies and costs of local externalities by fuel (in % of benchmark consumption).

Region	Fossil fuel subsidies			Local externalities		
	Refined oil	Natural gas	Coal	Refined oil	Natural gas	Coal
ARG	0.40	0.10	0.00	2.70	0.10	0.10
AUS	—	—	—	3.00	0.00	0.20
BRA	—	—	—	2.60	0.00	0.10
CAN	—	—	—	4.20	0.10	0.10
CHN	0.30	—	—	6.10	0.10	25.90
DEU	—	—	—	3.00	0.10	1.10
FRA	—	—	—	3.50	0.10	0.30
GBR	—	—	—	2.30	0.10	0.30
IDN	2.20	—	—	4.50	0.10	1.20
IND	1.10	0.10	—	7.70	0.00	7.40
ITA	—	—	—	2.60	0.10	0.10
JPN	—	—	—	6.70	0.30	0.50
KOR	—	—	0.00	8.90	0.40	2.80
MEX	0.00	—	—	3.70	0.00	0.10
RCIS	1.30	2.10	0.70	6.20	0.60	11.70
REDA	0.20	0.10	0.00	4.30	0.10	1.90
REU	—	—	—	4.40	0.10	3.20
RLAC	0.90	0.10	—	5.10	0.00	0.10
RMEN	3.20	2.20	—	4.10	0.10	0.10
ROTW	0.00	—	0.00	4.70	0.40	1.50
RSSA	0.10	0.00	—	2.10	0.00	0.00
RUS	—	1.30	—	22.90	2.70	7.30
SAU	7.50	1.50	—	12.80	0.30	—
TUR	—	—	—	9.00	0.10	3.20
USA	—	—	—	2.50	0.20	0.70
ZAF	—	—	—	7.20	—	2.50
World	0.30	0.13	0.01	4.48	0.19	4.18

Table C.4. Descriptive statistics on percentage changes in welfare, consumption, and local externalities under different policy scenarios.

Region	Welfare change (%)				Consump. change (%)		Local Ext. change (%)	
	Subsidy removal	NPOLL	LPOLL	Removal & Full	Subsidy removal	Removal & Full	Subsidy removal	Removal & Full
ARG	0.06	0.24	0.22	0.20	-0.07	-0.63	0.13	0.83
AUS	0.00	0.38	0.30	0.43	0.00	-0.59	0.00	1.02
BRA	-0.00	0.04	0.15	0.01	-0.00	-0.61	0.00	0.62
CAN	-0.00	0.63	0.37	0.67	-0.00	-0.78	0.00	1.45
CHN	0.49	3.40	18.77	19.40	0.00	-10.66	0.48	30.06
DEU	-0.00	0.30	0.09	0.16	-0.00	-1.26	0.00	1.42
FRA	-0.00	0.11	0.13	0.06	-0.00	-1.12	0.00	1.18
GBR	0.00	-0.06	0.09	-0.05	0.00	-0.72	-0.00	0.67
IDN	1.53	1.76	1.72	2.76	0.46	0.06	1.08	2.69
IND	0.64	2.42	3.44	5.05	-0.01	-2.99	0.66	8.04
ITA	-0.00	-0.05	0.01	-0.18	-0.00	-0.88	0.00	0.69
JPN	-0.00	1.42	1.05	1.45	-0.00	-1.95	-0.00	3.40
KOR	0.02	3.02	3.39	4.51	0.00	-1.39	0.01	5.90
MEX	0.00	0.56	0.52	0.70	0.00	-0.33	0.00	1.04
RCIS	2.71	1.81	9.03	9.88	0.64	-2.34	2.07	12.22
REDA	0.13	1.01	1.13	1.79	0.02	-0.61	0.11	2.39
REU	-0.00	0.83	1.91	2.33	-0.00	-1.52	0.00	3.85
RLAC	0.42	1.05	0.80	1.26	0.04	-0.69	0.39	1.95
RMEN	1.36	1.17	0.55	1.80	0.51	0.15	0.85	1.64
ROTW	0.04	1.03	2.23	2.72	0.01	-0.12	0.03	2.85
RSSA	0.04	0.31	0.08	0.32	0.00	-0.20	0.03	0.52
RUS	0.28	9.58	22.44	22.89	0.09	-7.53	0.18	30.42
SAU	4.00	4.87	3.12	6.60	1.22	-0.19	2.78	6.79
TUR	-0.00	1.33	1.30	1.98	-0.00	-3.87	0.00	5.85
USA	-0.00	0.34	0.28	0.44	-0.00	-0.62	0.00	1.05
ZAF	-0.00	2.09	1.20	2.49	-0.00	-1.25	0.00	3.74

Notes: Values represent percentage changes relative to a baseline scenario ("No reform") for the respective policy measures.

Download ZEW Discussion Papers:

https://www.zew.de/en/publications/zew-discussion-papers

or see:

https://www.ssrn.com/link/ZEW-Ctr-Euro-Econ-Research.html
https://ideas.repec.org/s/zbw/zewdip.html

//
IMPRINT

ZEW – Leibniz-Zentrum für Europäische Wirtschaftsforschung GmbH Mannheim
ZEW – Leibniz Centre for European Economic Research

L 7,1 · 68161 Mannheim · Germany
Phone +49 621 1235-01
info@zew.de · zew.de