Efficiency, Distributional, and Fiscal Effects of Climate Policy: The Case of Fossil Fuel Subsidies and Externalities

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By Tim Kalmey and Sebastian Rausch*

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The global public good nature of climate change mitigation and the resulting free-rider problem require a restructuring of the incentives for countries to price fossil energy consumption. Existing empirical evidence unequivocally documents the large magnitude of fossil fuel subsidies in terms of prices warranted by supply costs and local damages related to fossil energy use. This paper examines the efficiency, distributional, and fiscal effects at the regional and global level from removing explicit and implicit fossil fuel subsidies, the latter entailing Pigouvian pricing of major local externalities, and carbon pricing to achieve countries' Paris climate targets.

To perform counterfactual analysis, we develop a multi-sector multi-region general equilibrium model that incorporates granular data on fossil fuel subsidies, undercharging supply cost as well as marginal local external costs of fossil energy use by type of externality, fuel, economic sector, and country with national income and product accounts data, including information on bi-lateral international trade flows to capture international market responses and global supply chains related to fossil fuels.

Removing explicit subsidies yields small welfare gains, while local Pigouvian energy pricing generates average gains of 4.3%, with country-level gains ranging from 5-25%. Pricing externalities from local air pollution captures 86% of these benefits. We also examine the impacts from subsidies removal on public budgets: fiscal revenues from removing both explicit and implicit subsidies amount to 5.1% of global consumption, or USD 2.4 trillion per year. Unilateral subsidy removal lowers the shadow cost of carbon by 86%, helping about 40% of countries, including the top CO_2 emitters (US, China, India), surpass their Paris targets, while generating significant welfare gains. Unrealized welfare gains from underpricing fossil energy total 2.7% of global consumption, with 90% due to local air pollution. Our analysis points to strong unilateral incentives for countries to eliminate explicit and implicit fossil fuel subsidies while contributing to the global public good of climate change mitigation. These incentives are reinforced when using the fiscal revenues from local energy pricing to lower pre-existing distortionary labor taxes. Finally, we find that local Pigouvian energy pricing can have unintended distributional effects across countries: while removing fossil fuel subsidies always is a dominant strategy from a unilateral perspective, a country's action can trigger negative welfare effects for other countries through internationally linked product markets.

I. Introduction

A. Motivation, Focus, and Contribution

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 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 requires a restructuring of the underlying incentives.

In this paper, we examine the incentives for reducing fossil energy consumption at the local (i.e. country or regional) level when the global climate externality is ignored. We do this by analyzing the efficiency, cross-country distributional, and fiscal effects of climate policies which entail getting prices of fossil energy right, including carbon pricing as required to achieve countries' Paris climate targets. 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 still heavily subsidize fossil fuels, both explicitly (undercharging supply costs) and implicitly (undercharging environmental costs). 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] 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. This paper investigates three main questions: What are the incentives for countries and regions to eliminate existing fossil fuel subsidies and adopt prices for fossil energy which reflect supply and environmental cost? How large are the foregone welfare gains from the subsidized use of fossil fuels in today's economies? How far would the removal of fossil fuel subsidies take individual countries and the global community in achieving their climate targets (as called for in the Paris Climate Agreement)?

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

We contribute by providing the first study on the welfare effects of explicit and implicit fossil fuel subsidies in a multi-country multi-sector quantitative general equilibrium framework, accounting for market and non-market welfare and the role of fossil energy in global supply chains linked by intermediate and end products and international trade. Previous studies have focused either on explicit fossil fuel subsidies only (Jewell et al., 2018; Chepeliev and van der Mensbrugghe, 2020; Arzaghi and Squalli, 2023) or, when analyzing implicit subsidies, used partial equilibrium models for individual countries' fossil fuel markets (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).

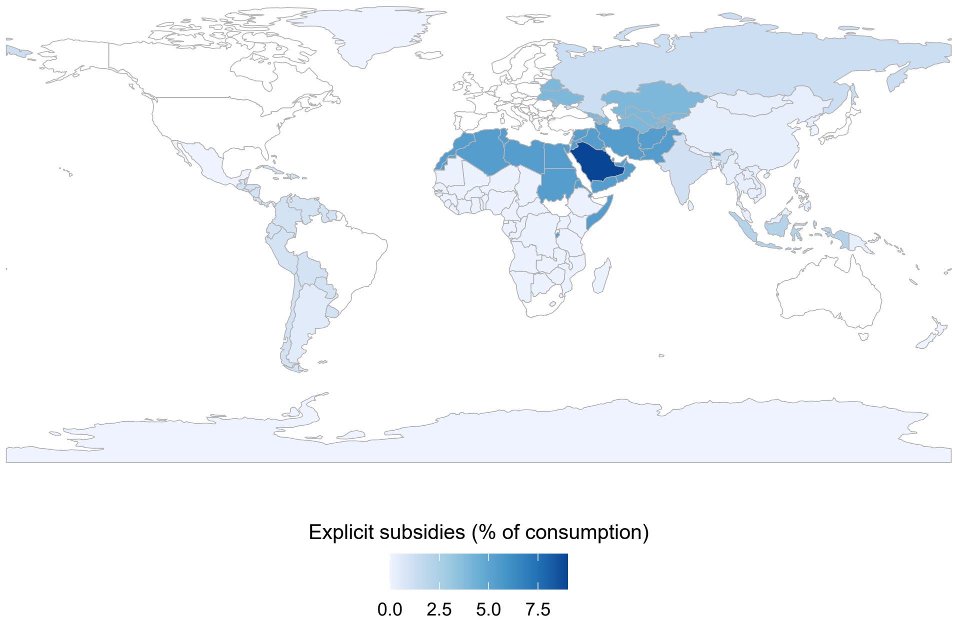
B. Empirical-quantitative Multi-sector Multi-region General Equilibrium Framework

We argue, and provide evidence, that a multi-region multi-commodity general equilibrium perspective is essential: fossil fuels are highly interwoven with the production and consumption of goods and services, fossil fuels themselves and goods produced with them are traded, making markets and economies deeply linked both domestically and internationally in response to public policy choice regarding the continuation or phase-out of fossil fuel subsidies. In addition, non-market effects of reducing fossil energy use are tied to physical quantities of coal, oil, and gas. Evaluating fossil fuel subsidies requires a framework that not only tracks economic efficiency and market welfare, but also changes in physical energy flows.

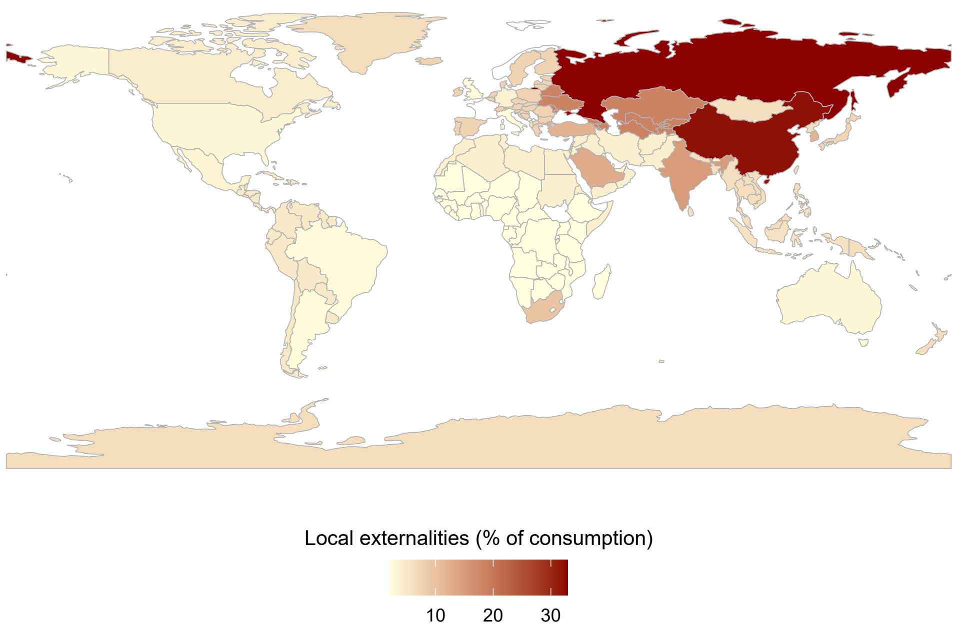
Our structural equilibrium model integrates granular data on explicit and implicit fossil fuel subsidies from the IMF database (Parry et al., 2014; Coady et al., 2017) and the Global Trade Analysis Project (Chepeliev, McDougall and van der Mensbrugghe, 2018; Aguiar et al., 2022) with national income and product accounts data, including information on bi-lateral international flows. The data and our model resolve the marginal local external costs of consumption of oil (gasoline, diesel, kerosene), coal, and natural gas, distinguished by fuel by sector of use, and by type of local externality.[2] Local externalities differentiate health effects from elevated mortality risks from local air pollutants, attributed separately to the major pollutants released when burning fossil fuels, namely 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 associated with congestion, accidents, and (less importantly) road damage. We examine not only the welfare implications of unilateral price reform for the major EU countries, a regional aggregate for Europe, and 16 non-European countries and five world regions, but also a counterfactual world in which all countries and regions jointly eliminate explicit and implicit fossil fuel subsidies.

[2]The model is based on multi-sector multi-country general equilibrium developed for deliverable D4.5, connected to Task 4.6, of the WeLaR project. Here, we use a static version of the model with a simplified demand structure (i.e., assuming a representative agent by country), but add considerable detail in terms of sectors, fossil energy use, direct fossil fuel subsidies, and local externalities related to fossil energy use.

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



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

C. Counterfactual Experiments

The granular data and detail of the structural equilibrium model enables us to perform counterfactual analysis, deriving novel insights into fossil fuel subsidy reform and local Pigouvian energy pricing. We define local Pigouvian energy pricing as the price of a fossil fuel used in a given sector in a region which fully reflects the supply cost and external damages associated with multiple fossil-energy related local externalities. We examine not only the welfare implications of unilateral price reform for the major 19 countries and six world regions, but also a counterfactual world in which all countries and regions jointly remove explicit and implicit fossil fuel subsidies. While global implementation of local Pigouvian energy pricing is hypothetical, it serves to estimate the unrealized welfare gains from using fossil fuels without accounting for their full cost in a global economy that still heavily relies on fossil energy. It also highlights the balance between a country's self-interest in addressing local externalities and its role in global climate change mitigation.

D. Summary of Main Results

EFFICIENCY AND DISTRIBUTIONAL EFFECTS.—We find that the removal of explicit fossil fuel subsidies yields only small welfare gains for most countries (0.2% on average), with the exception of countries characterized by high existing explicit subsidies (mainly Middle Eastern and North African countries), which experience somewhat larger gains. Unilateral local Pigouvian energy pricing, which also removes explicit subsidies, would yield large benefits for all countries and regions (on average 3.9%). Countries or regions with high marginal damages per unit of fossil energy use or a high energy intensity of consumption (including many European countries, China, India, Saudi Arabia, Russia and members of the Commonwealth countries) would experience substantial gains on the order of 5-23%. In contrast, major EU countries like Germany and France would only slightly gain from Pigouvian pricing (less than 0.2%) or even be worse off such as Italy. Pricing only externalities related to local air pollution would reap already, on average across countries, 75% of the welfare benefits. Pricing non-pollutant local externalities yields higher benefits than removing explicit fossil fuels subsidies but considerably smaller gains than internalizing local air pollution (on average 1.3%). Removing explicit subsidies reduces market distortions, boosting both market and non-market welfare. Removing implicit subsidies increases non-market welfare but lowers market welfare in most countries due to higher energy prices. Apart from quantitatively negligible exceptions, overall, countries experience a positive net welfare effect, with the magnitude depending on the relative size of marginal damages and energy intensity of consumption.

For European countries, local Pigouvian pricing would increase welfare by 0.9%, on average, while pricing local air pollution and non-pollutant externalities entails welfar gains of 0.8% respectively 0.4%. Indeed, these enhancements are mainly driven by the rest of Europe aggregate (2.3%) as major EU countries Germany and France would only slightly gain (less than 0.2%) from Pigouvian pricing or even be worse off such as Italy. These regions are strictly better off achieving reductions in fossil energy use through local Pigouvian pricing policies rather than implementing climate policy. This is particularly the case for Germany and other European countries, while Paris 2°C compatible carbon prices in France and Italy would be lowered by more than 50%.

FISCAL EFFECTS ON PUBLIC BUDGETS.—We also estimate the impact on public budgets resulting from the removal of direct and indirect fossil fuel subsidies. Fiscal revenues generated from removing explicit and implicit fossil fuel subsidies would be substantial. On average, countries or regions would obtain revenues equal to 4.9% of consumption, ranging from 1.8–16.2% at the regional level. Removing explicit fossil fuel subsidies would, on average, create only fiscal revenues equal to 0.4% of consumption per year. Major EU countries (Germany, France, Italy) can also expect substantial inflows for the public budget from local Pigouvian pricing ranging from 2.1 to 2.9% (billion $26–59) while the rest of Europe may even collect amounts totaling 4.3% (billion $192). Summing over all countries and regions, we estimate that the total fiscal revenues from local Pigouvian energy pricing would amount to trillion $2.5 per year.

Major EU countries (Germany, France, Italy) can also expect substantial inflows for the public budget from local Pigouvian pricing ranging from 2.1 to 2.9% (billion $26–59) while the rest of Europe may even collect amounts totaling 4.3% (billion $192). When taking a closer look at European countries, France, Germany, United Kingdom and other European countries can expect substantial inflows for the public budget from local Pigouvian pricing of 3.2% of consumption (billion $103), on average, totalling billion $359 per year (billion $216 from pollutant and $142 from non-pollutant externality pricing).

Using these revenues for labor tax reductions can further enhance the welfare benefits of local Pigouvian pricing as compared to lump-sum per capita recycling. We estimate that welfare benefits are on average 0.16 percentage points higher compared to the case in which revenues are recycled with a lump-sum per capita approach. Particularly major EU countries Germany (0.28 p.p.) France (0.40) and Italy (0.24) may benefit from recycling revenues for labor tax reduction as well as the rest of Europe (0.36), all with above average welfare gains.

CO-BENEFITS FOR CLIMATE CHANGE MITIGATION.—We document quantitatively significant co-benefits for climate change mitigation from unilaterally removing fossil fuel subsidies. While the unilateral removal of explicit fossil fuel subsidies would have only minor effects on a country's shadow cost of carbon to meet Paris climate targets, eliminating implicit subsidies would, on average, reduce country-level carbon prices by 76%. About 50% of countries and regions would already over-achieve their Paris target, implying that the required carbon price to meet the Paris climate target reduces to zero. Importantly, most countries and regions reduce their cost of achieving climate targets when combining climate policy with local Pigouvian energy pricing: on average, we estimate a welfare gain of 3 percentage points or 429%. For countries with over-fulfillment of climate targets, our analysis suggests that they are strictly better off pricing local externalities related to fossil energy use, rendering climate policy redundant. This is also the case for Germany and other European countries, while Paris 2°C compatible carbon prices in France and Italy would be lowered by more than 50%.

If all countries and regions removed explicit and implicit fossil fuels subsidies, we estimate that global CO_2 emissions would be reduced by 32%. Global pricing of local externalities related to air pollution alone would reduce global CO_2 emissions by 26% and thus already meet the amount required by the Paris Agreement in line with a 2°C warming target. About 40% of the countries or regions, including India, China, Russia and Rest of Europe would already reach their Paris target. Other industrialized and energy-importing countries like Germany, US, France, Japan and United Kingdom would already achieve a substantial fraction (more than 50%) of their Paris target through local Pigouvian energy pricing. We find that local Pigouvian energy pricing can have unintended distributional effects across countries. While removing fossil fuel subsidies always is a dominant strategy from a unilateral perspective, a country's action can trigger negative welfare effects for other countries through internationally linked product markets. Fossil energy exporters face welfare losses as global demand for fossil imports declines. For oil exporters like RCIS, RMEN, and Saudi Arabia, local energy pricing for oil-related transport use has the largest welfare impact. However, these losses are mitigated or offset when subsidy removal and comprehensive pricing scenarios are considered, especially for RCIS. Similarly, coal exporters like Indonesia, Australia, and Canada face welfare losses as coal demand drops. In contrast, Russia and South Africa gain more from pricing their local pollutant externalities than they lose from reduced coal trade. If all countries implemented Pigouvian energy pricing, major EU countries (Germany, France, Italy) would experience losses in market-based welfare and increases from reduced local damages (non-market welfare gains), leaving them largely unaffected overall. In comparison, the rest of Europe, characterized by relatively high monetized local damages per physical unit of fossil fuel used, would overall benefit.

Finally, we estimate that the welfare cost from using fossil energy in an unregulated manner in today's global economy amounts to 2.4% of global consumption. Just by pricing local externalities related to air pollution would reap more than 90% of these welfare gains, yielding a global welfare gain of 2.3%. The effects from removing explicit fossil fuel subsidies are relatively small if measured at global scale, with a welfare gain of 0.1%.

E. Structure of the Paper

This paper proceeds as follows. Section II describes our model and defines concepts for local Pigouvian energy pricing. Section III presents data sources and discussed model calibration. Section IV provides a descriptive analysis of fossil energy subsidies and local externalities using the observational data which underlies our structural model. Section V presents our design of counterfactual experiments. Section VI scrutinizes the role international trade and global supply chains for assessing the removal of fossil fuel subsidies. Section VII presents and discusses our main results. Section VIII concludes. Appendices contain additional information and analyses.

II. The Model

A. Measuring Welfare and Emissions

Our welfare assessment is based on a comprehensive global-economy general equilibrium framework which incorporates the domestic production and consumption responses and the international market effects from local energy pricing reform. Equilibrium prices and quantities $(\boldsymbol{p}, \boldsymbol{q})$ are derived from a multi-region, multi-sector, multi-commodity general equilibrium (GE) model which takes policy choices with respect to local energy pricing as exogenously given.

The regulator in the $r \in \mathcal{R}$ region 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. Subsidies are paid for the use of fossil fuel of type $f \in \mathcal{F} = \{Coal, Natural\ gas, Oil\}$ 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 $\mathcal{N} = \{Congestion, Accidents, Road\ damages\}$. 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 elsewhere in the global economy):

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

U_r measures local economic welfare (excluding damages from local externalities) in money metric utility based on the equilibrium level of private extended consumption C_r of the representative consumer in region r. Extended consumption C_r includes material consumption and leisure consumption, with the latter creating the endogenous labor supply.

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:

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

$\overline{m}_{xfgr}$ 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. 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 $q_{fgr}^{\textit{Fossil energy used}}$ consistent with economic equilibrium decisions.

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[3]:

$$(3) \qquad CO2 = \sum_{f \in \mathcal{F}, g \in \mathcal{G}, r \in \mathcal{R}} \overline{e}_{fgr} \times q_{fgr}^{\textit{Fossil energy used}} [\boldsymbol{q}(\boldsymbol{\tau}, \boldsymbol{s}), \boldsymbol{p}(\boldsymbol{\tau}, \boldsymbol{s})]$$

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

B. Local Energy Pricing

Fossil fuels are used as inputs in local production and consumption activities. Local energy subsidies and taxes are levied on an ad-valorem basis at the point of burning fossil fuels in production and consumption (for example, firing coal for electricity, the use of refined oil for transport services or natural gas for domestic 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 2 illustrates the nested structure):

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

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 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 $\boldsymbol{s} = \{s_{fgr}^Y, s_{fgr}^M\}$.

[3]In this paper, we focus only on the climate benefits that would result from reducing CO_2 emissions from the burning of fossil fuels. We leave it to future research to investigate the inclusion of non-CO_2 greenhouse gas emissions and process emissions. For the case of analyzing local co-benefits of climate policy, non-CO_2 have been surveyed, for example, by Vandyck et al. (2018) and Anenberg et al. (2012).

The user cost (per unit of energy) of fossil fuel f in sector g and region r, c^A_{fgr}, which includes fossil fuel subsidies and taxes to address local externalities, is given by:

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

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 cost of 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:

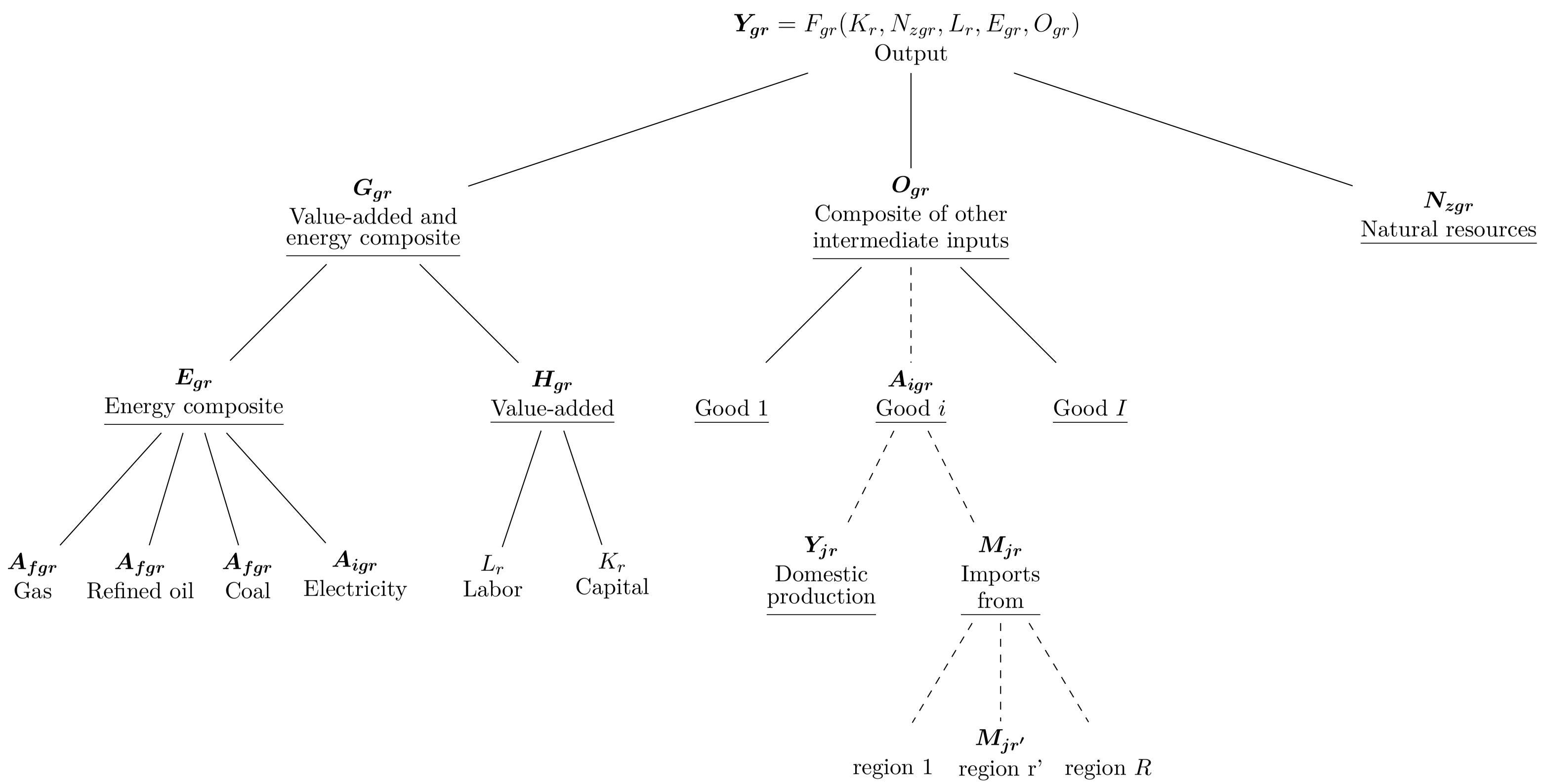
DEFINITION 2: ***(Local Pigouvian energy prices)*** *The local price of fossil fuel f used in sector g in region r fully reflects the supply cost and external damages associated with the presence of multiple fossil-energy related local externalities, i.e. the user cost of fossil energy c^A_{fgr} involves 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 difficulties of determining the social cost of carbon, especially when multiple countries are involved, we refrain from theoretical "full" Pigouvian pricing and instead take a different approach. We use the CO_2 emissions reduction goals, or Nationally Determined Contributions (NDCs), set by countries under the Paris Agreement, scale them to be compatible with 2°C of global warming 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 ($\delta_r = \pi_r$).*

FIGURE 2. Structure of domestic production for sectoral good Y_{gr}



C. Global Supply Chains, International Trade, and Markets

To measure the welfare effects from alternative local energy pricing structures, we use a multi-region multi-commodity Arrow-Debreu GE model of the global economy 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.[4]

DOMESTIC PRODUCTION AND FINAL GOOD AGGREGATION.—Product and factor markets are perfectly competitive, and there is free entry and exit. 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 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 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}.

[4] 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: $\mathbb{R}^n \longrightarrow \mathbb{R}^n$, 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 $z = 0$.

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:

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

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.[5] 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 2).

At the first stage, imports from different regions are aggregated. The equilibrium

[5] 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*a*) 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 $\sum_i \theta_i = 1$.

level of aggregate imports of good i in region r, M_{ir}, is determined by:

$$c^M_{ir} = \left(\sum_{r'} \theta^M_{ir'r} (p^Y_{ir'})^{(1-\sigma^M_{ir})}\right)^{1/1-\sigma^M_{ir}} \geq p^M_{ir} \quad \perp \quad M_{ir} \geq 0\,. \tag{11}$$

where $\theta^M_{ir'r}$ 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^M_{ir} 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:

$$c^A_{igr} \geq p^A_{igr} \quad \perp \quad A_{igr} \geq 0\,. \tag{12}$$

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:

$$Y_{ir} \quad \geq \quad \sum_g A_{igr} \frac{\partial c^A_{igr}}{\partial p^Y_{ir}} + \sum_{r'} M_{ir'} \frac{\partial c^M_{ir'}}{\partial p^Y_{ir}} \quad \perp \quad p^Y_{ir} \geq 0 \tag{13a}$$

$$A_{igr} \quad \geq \quad Y_{gr} \frac{\partial c^Y_{gr}}{\partial p^A_{igr}} \quad \perp \quad p^A_{igr} \geq 0 \tag{13b}$$

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

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:

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

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

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.

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

$$c^M_{ir} = p^{World}_i \geq p^M_{ir} \quad \perp \quad M_{ir} \geq 0 \tag{11$'$}$$

$$Y_{ir} \geq \sum_g A_{igr} \frac{\partial c^A_{igr}}{\partial p^Y_{ir}} + M^{World}_i \frac{\partial c^{M,World}_i}{\partial p^Y_{ir}} \quad \perp \quad p^Y_{ir} \geq 0 \tag{13a$'$}$$

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

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

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

where π_r is the regional carbon price.

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). We also consider a scenario in which we recycle the revenues by lowering pre-existing labor taxes. 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 exogenous and given by respective benchmark levels $\overline{G}_r$ and $\overline{I}_r$ in each region, and 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 (1) Y_{gr}, M_{ir}, and A_{igr} maximize profits or minimize costs as in (7), (11), and (12) and (2) 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).

III. 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 (including labor taxes). We use version 11 of the GTAP database and the base year 2017.[6]

Table 1 shows the sectors and commodities, regions, and primary factors of the model. The model distinguishes four energy sectors (coal, natural gas, crude

[6]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*b*).

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) (see p. 24, Table 2). The sectoral and regional mappings are available on request from the authors.

oil, refined oil) 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.

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.

B. *Physical energy flows and CO_2 emissions*

We make use of the 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 thus 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): $q_{fgr}^{Fossil\ energy\ used} = \overline{ev}_{fgr} \times A_{fgr}$. 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).

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

Starting from version 11, GTAP already includes consumer explicit subsidies for fossil fuels in their commodity-specific tax rates following the procedure in Chepeliev, McDougall and van der Mensbrugghe (2018).[7] 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 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;

[7]Note that energy subsidies in GTAP11 are based on data from the the International Energy Agency (IEA) unlike described in Chepeliev, McDougall and van der Mensbrugghe (2018)/ GTAPes which uses IMF data.

(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 Climate Targets

We derive climate targets (NDCs) of countries compatible with limiting global warming to 2°C by computing required percentage redcutions in CO_2 emissions between our model base year 2017 and 2030.[8] For this, we use results of the EU Commission model JRC-POLES that are presented in the Global Energy and Climate Outlook 2020 (Keramidas et al., 2021). The report provides country-level estimates of CO_2 emissions from fuel combustion for the years 2015, 2020 and 2030 that are compatible with limiting global warming with a probability of 67% to 2°C as envisaged by the Paris Agreement from 2015. We take 2015 and 2020 emission estimates and interpolate 2°C compatible CO_2 emissions for our model base year 2017 assuming a constant emission growth rate. Based on these emission estimates, we finally compute for each country the percentage reduction in CO_2 between 2017 and 2030 required to limit global warming to 2°C (NDC Paris2C) which are depicted in Figure 11.

IV. 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 3 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 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,

[8]2030 is the year aginst which most NDCs submitted by countries to the UNFCCC in the course of the Paris Agreement are formulated.

FIGURE 3. Global explicit and implicit fossil fuel subsidies by energy product and subsidy component

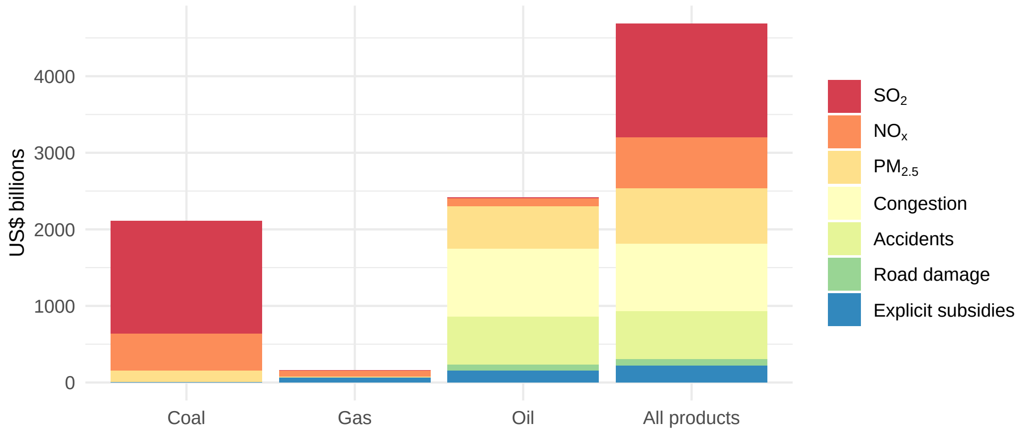
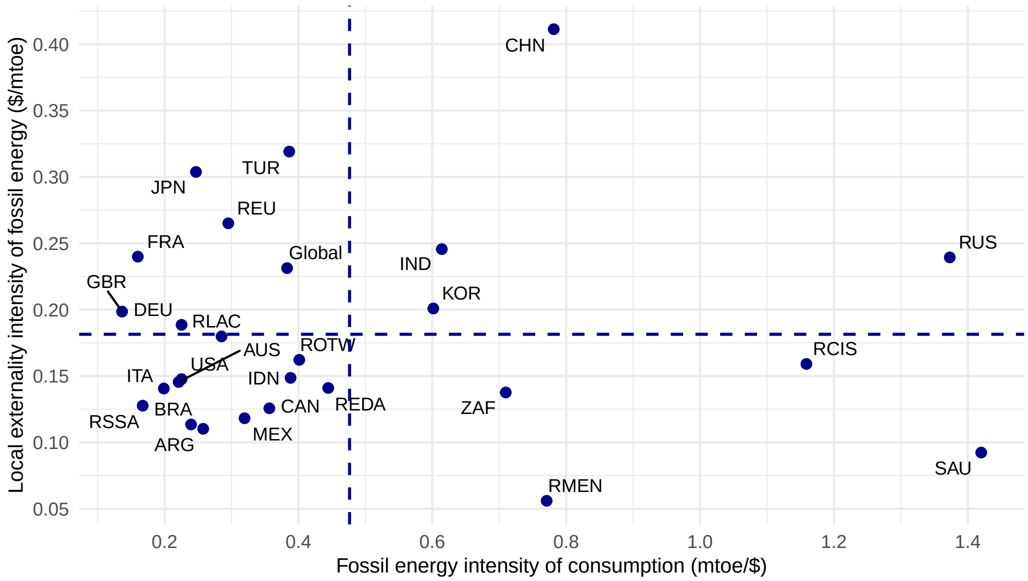


TABLE 2. Descriptive statistics on consumption, volume of fossil fuel subsidies, aggregate costs of local externalities, and CO_2 emissions.

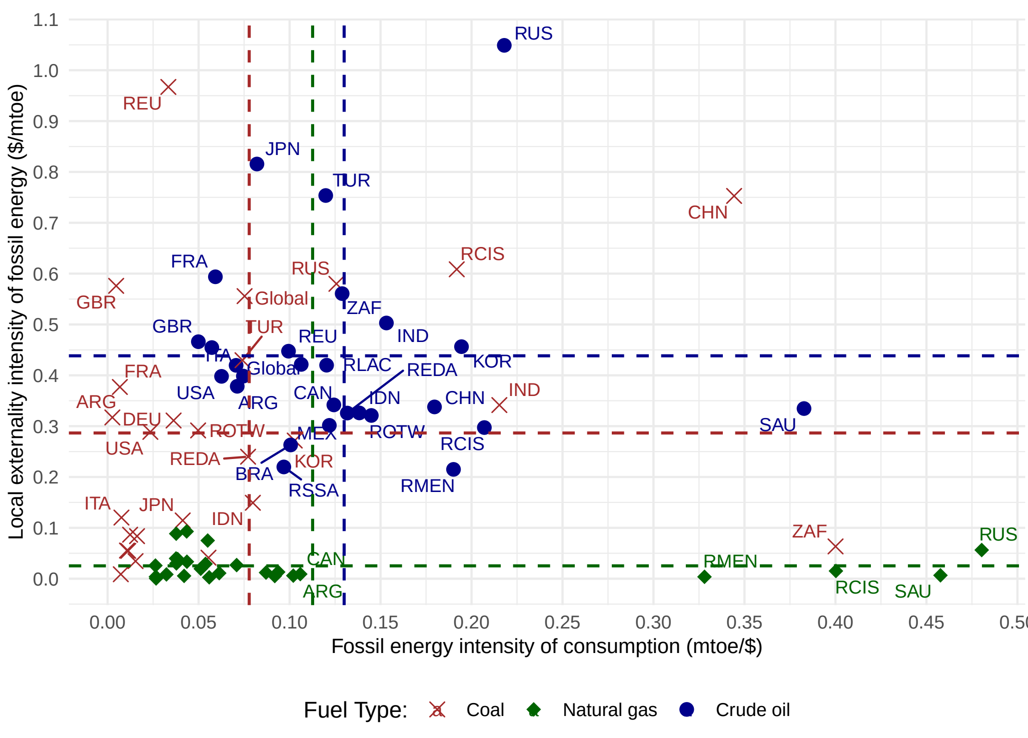
Region	Consumption	Explicit fossil fuel subsidies		Combined local externalities		Ratio[1]
	bill. $2017	bill. $2017	% of cons.	bill. $2017	% of cons.	
ARG	466.0	2.4	0.5	13.2	2.8	0.2
AUS	811.9	—	—	26.1	3.2	0.4
BRA	1411.3	—	—	38.4	2.7	0.5
CAN	1056.4	—	—	47.3	4.5	0.6
CHN	5733.7	18.1	0.3	1842.7	32.1	9.4
DEU	2045.0	—	—	86.9	4.2	0.8
FRA	1530.2	—	—	58.7	3.8	0.3
GBR	1950.0	—	—	52.8	2.7	0.4
IDN	615.2	13.3	2.2	35.5	5.8	0.5
IND	1806.6	20.3	1.1	272.5	15.1	2.2
ITA	1241.6	—	—	34.7	2.8	0.3
JPN	2870.1	—	—	215.2	7.5	1.1
KOR	818.4	0.1	0.0	98.9	12.1	0.6
MEX	787.3	0.1	0.0	29.7	3.8	0.4
RCIS	339.6	13.6	4.0	62.6	18.4	0.7
REDA	1303.8	4.3	0.3	81.7	6.3	1.1
REU	4485.4	—	—	350.9	7.8	1.9
RLAC	1400.4	13.4	1.0	71.8	5.1	0.6
RMEN	1758.2	95.1	5.4	75.9	4.3	2.0
ROTW	926.1	0.3	0.0	60.3	6.5	0.5
RSSA	905.4	1.1	0.1	19.3	2.1	0.3
RUS	877.2	11.5	1.3	288.3	32.9	1.6
SAU	309.4	27.8	9.0	40.6	13.1	0.5
TUR	532.3	—	—	65.6	12.3	0.4
USA	14190.9	—	—	472.1	3.3	5.0
ZAF	245.3	—	—	24.0	9.8	0.4
World	50417.7	221.4	0.4	4465.7	8.9	32.7

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). [1]:Ratio is calculated by dividing the size of combined local externalities by the size of explicit fossil fuel subsidies.

Figure 4. 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.

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.[9] They are most prevalent in the Middle East, North Africa, and the RCIS, reaching up to 9% of consumption. Local externalities are particularly high in China, Russia, and many Asian and Middle Eastern countries but also not negligible in many European, primarily Eastern European, countries.[10]

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

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

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 4 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

[9]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.

[10]Table A1 in an appendix provides further detail on the size of fossil fuel subsidies and local externalities by region and by type of fossil fuel.

Table 3. Design of counterfactual experiments

Dimension	Specifications	Name
Fossil fuel subsidy removal		
Explicit subsidies		
	Fossil fuel subsidies	Subsidy removal
Local externality pricing (implicit subsidies)		
	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
Revenue recycling scheme		
	Lump-sum per capita	Lump-sum
	Labor tax reduction	LabTax
International trade closure		
	Small open economy	SOE
	Multi-regional trade	MRT
Climate mitigation policy		
	CO_2 emissions reductions according to NDCs under Paris agreement	Paris

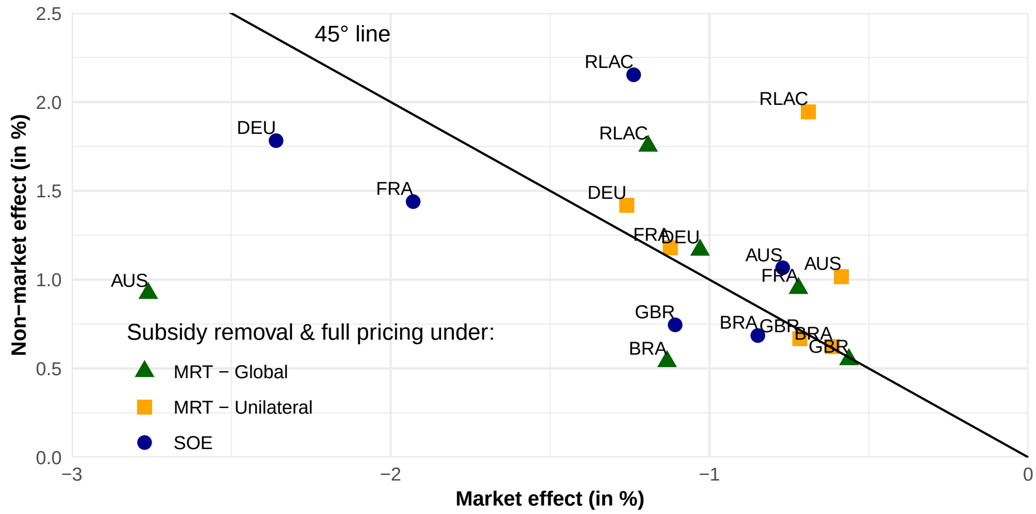
with oil use and a relatively low intensity associated with coal. This suggests that the regional variation in the externality intensity of aggregated fossil energy use is largely driven by the between-country differences for the same fossil fuel.

V. Counterfactual Experiments

We analyze the welfare effects of getting local energy prices right, which involves removing both explicit subsidies (see Definition 1) and implicit subsidies on fossil fuels. The latter is equivalent to taxing local externalities related to fossil energy use according to marginal damage. The combined removal of explicit and implicit subsidies represents local Pigouvian pricing (see Definition 2).

Table 3 summarizes the dimensions and specifications of our counterfactual experiments. To analyze the quantitative importance of the individual subsidy components, our counterfactual analysis first dissects explicit subsidies and then assesses the pricing of local air pollutants and, finally, local non-pollutant externalities. In addition, we explore the welfare effects if a country or region were to unilaterally remove subsidies (i.e., in all other regions, existing explicit subsidies remain unchanged and local externalities are not priced at all). This helps to obtain insights into the unilateral incentives of subsidy reform for different countries and regions. A hypothetical situation would be the worldwide elimination of fossil fuel subsidies, i.e. all countries and regions would jointly introduce local Pigouvian energy prices. Nevertheless, such a counterfactual perspective is valuable because it provides an estimate of the foregone welfare gains embedded in today's globalized economy, whose economic activity is hardwired to the use of fossil energy. We also investigate how the recycling scheme of revenues generated through local Pigouvian

FIGURE 5. Decomposition of welfare effects from local energy pricing into market and non-market effects under alternative international trade closures



pricing may affect outcomes. As default we apply in the majority of the scenarios lump-sum per capita recycling but also examine how labor tax reduction affects welfare.

Fossil fuels are inextricably linked to economic output and welfare through global supply chains for goods and services. To scrutinize the importance of international markets and linkages in a global economy for assessing local Pigouvian energy pricing, an additional dimension of our counterfactual experiments considers varying the international trade closure of our equilibrium model. In a small-open economy setting, a country or region is unable to pass-forward costs of higher energy prices in international markets. At the same time, countries that are net exporters of fossil energy can be adversely affected if their major trade partners reduce energy imports due to removing fossil energy subsidies and taxing local externalities.

Finally, we are interested in examining how far local Pigouvian energy pricing would carry countries and region towards fulfilling their climate policy ambition. To provide a global context, we examine how getting energy prices right would affect a country's welfare and (shadow) price of carbon for achieving its NDC (Nationally Determined Contribution) submitted under the Paris Agreement.

VI. The Bias from Not Incorporating International Market Effects

To gauge the bias from not appropriately taking into account the response of international markets and global supply chains, we compare estimates from a small-open economy (SOE) model with those obtained from a multi-region trade (MRT) model. Overall, we find that the welfare effects estimated using the MRT model differ from the results of the SOE model in both sign and order of magnitude, in particularly at the country and regional level.[11]

The reason is that the SOE framework is lacking several important channels that govern an economy's adjustment in response to removing explicit and implicit fossil fuel subsidies. With the SOE assumption, prices of imports and exports are fixed, implying that it is not possible to pass-forward the cost of higher domestic energy prices (following the subsidy removal and pricing of local externalities). Figure 5 confirms this intuition: comparing SOE (blue points) to MRT–Unilateral (yellow squares) shows that the MRT model predicts that all countries are better off in from a subsidy removal and FULL externality pricing. Importantly, the welfare gains, comprising market and non-market effects is positive, i.e. all countries are above the 45° line. In contrast, the SOE economy predicts smaller welfare gains or even welfare losses for some countries. With the ability to pass-forward cost, countries with negative welfare effects under SOE (Germany, France, United Kingdom) can reduce their negative market effects by more than positive non-market effects are lowered.

When countries or regions jointly engage in removing fossil energy subsidies, the inadequacy of the SOE framework becomes even more apparent. As removing fossil fuel subsidies implies a contraction of demand on global energy markets, countries which are net energy exporters are negatively affected. In Figure 5, comparing SOE (blue points) to MRT–Global (green triangles) shows that energy-exporting countries (such as Australia, Saudia Arabia, Brazil) are worse off in terms of market effects.

On average, we find that the SOE economy model yields biased welfare estimates of 60% (102%) compared to the MRT model with unilateral (global) implementation of fossil fuel subsidy removal. At the country and regional level, welfare biases are substantial with up to 164% (253%) unilateral (global) implementation with a standard deviation of 399% (670%). Table A2 in an appendix reports the welfare changes by region from comparing the SOE and MRT model and calculates the bias in welfare estimates. Neglecting international market responses and global supply chains also leads to biased estimates for CO_2 emissions reductions. With MRT–Global, the removal of fossil fuel subsidies reduces global emissions by 32% compared to 37% under the SOE model (see Figure A1 in an appendix).[12]

Given that the SOE setting omits important channels needed to assess the welfare effects of fossil fuel subsidy removal in a globalized economy with interlinked goods and energy markets, we rely on the MRT model for our main analysis.

[11] The bias in terms of global (average) outcomes is less pronounced, suggesting that a global model without country and regional detail might provide a reasonable first-order estimate of the global outcomes of fossil subsidy removal.

[12] In SOE, sources of fossil energy-intensive products can shift towards imports when a local energy pricing reform is implemented. But regional policies do not affect international prices. In contrast, in MRT a global adoption of energy pricing reforms yields higher prices for fossil fuels and upstream products on international markets. This limits incentives to import from and shift production to other regions yielding consistently lower reductions in CO_2 emissions regionally and globally.

FIGURE 6. Welfare effects of unilateral local pricing of externalities by region by scope of externality pricing

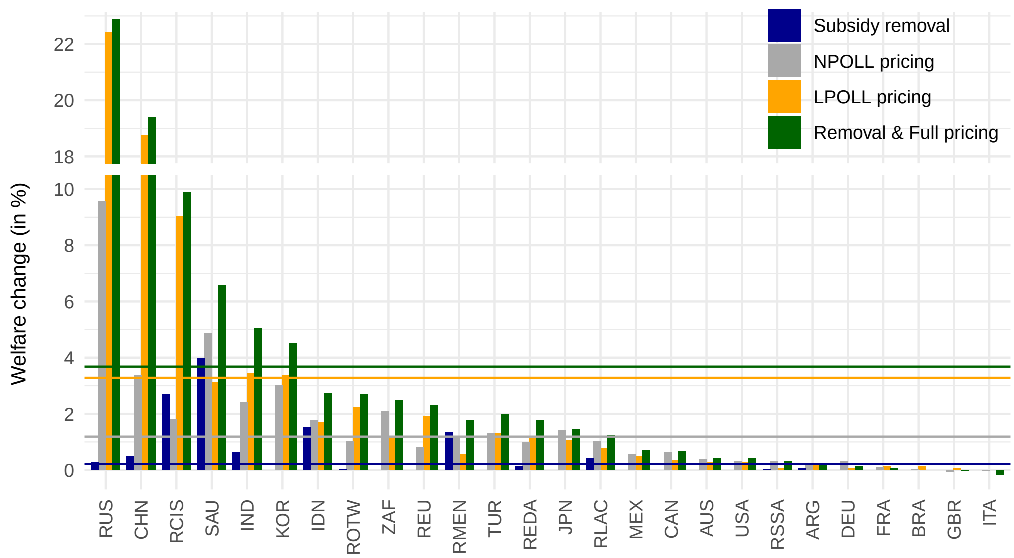
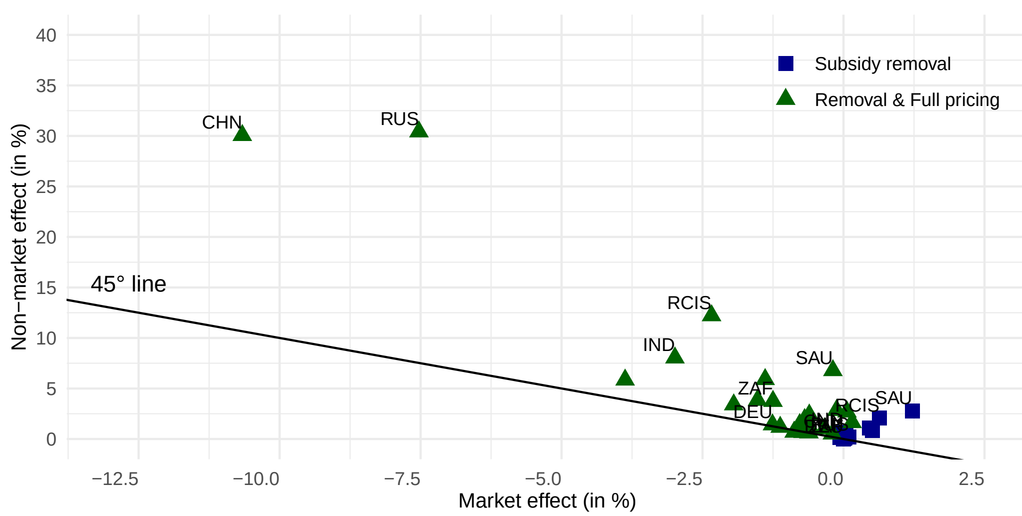


FIGURE 7. Decomposition of welfare effects from subsidy removal and full pricing of local externalities into market and non-market effects by region



VII. Main Results

This section presents our main results from counterfactual analysis using the general equilibrium model with multi-region trade and global supply chains.

A. Unilateral Local Pigouvian Energy Pricing

We first examine the incentives for individual countries to reduce fossil fuel subsidies and price local externalities associated with fossil fuels if other countries do not change their energy pricing policies. Given the difficulties and lack of internationally coordinated efforts to eliminate fossil fuel subsidies, let alone to implement a more comprehensive Pigouvian pricing of local externalities, unilateral pricing arguably best describes the decision problem countries are confronted with today. We examine a country's incentives for unilateral implementation using three different perspectives: (1) we assess the market and non-market welfare effects, (2) we quantify the fiscal revenues which could be obtained from getting energy prices right, and (3) we explore how local Pigouvian energy pricing alters the cost of achieving a country's climate target under the Paris agreement.

MARKET AND NON-MARKET WELFARE EFFECTS.—Figure 6 reports the welfare effects by country or region from unilaterally removing explicit and implicit fossil energy subsidies by scope of pricing. Several insights emerge. First, removing explicit fossil subsidies yields small welfare gains for most countries. On average, welfare gains are 0.2%. As the magnitude of explicit fossil fuel subsidies is small for most industrialized countries, welfare effects are also small. For a number of regions, however, welfare gains are substantial, including Saudi Arabia (4.0%), Commonwealth countries (RCIS) (2.7%), Indonesia (1.5%), and countries in the Middle East of North Afric (RMEN) (1.4%).

Second, adding Pigouvian pricing of local externalities (Removal & full pricing) yields large benefits with, on average, a welfare gain of 3.9%. Importantly, getting energy prices rights in a unilateral policy approach would improve welfare for every country or region except for Italy and United Kingdom.[13] Countries or regions that have a high intensity of fossil fuel use or a high energy intensity of consumption—i.e. China, India, Saudi Arabia, Russia and the RCIS, which are in the upper and lower right quadrants defined by the global averages in Figure 4—would experience significant welfare gains of 5-23% from local Pigouvian energy pricing.

Third, pricing only externalities related to local air pollution (LPOLL) would reap already most of the welfare benefits, with an average of 3.3%, i.e.75% (=3.3/4.4) of welfare gains can on average be attributed to local air pollution. Notably, for China and Russia Pigouvian pricing of externalities related to local air pollution would generate substantial welfare gains of about 20%. Fourth, pricing non-pollutant local externalities enhances welfare on average by 1.3%. Nevertheless, it is the most effective single policy in multiple regions like Saudi Arabia, South Africa, Canada or Germany.

For European countries local Pigouvian pricing would increase welfare by 0.9%, on average, while pricing local air pollution and non-pollutant externalities entails welfar gains of 0.8% respectively 0.4%. Indeed, these enhnacements are mainly driven by the rest of Europe aggregate (2.3%) as major EU countries Germany and France would only slightly gain from Pigouvian pricing (¡0.2%) or even be

[13] This changes if multiple countrie or regions enact a energy pricing reform. We consider this case below.

worse off such as Italy.

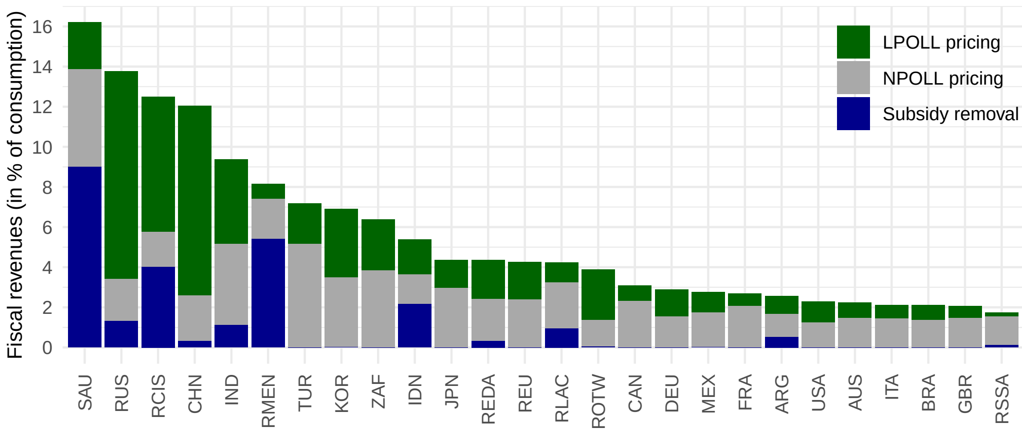
Using the definition of welfare in (1), Figure 7 decomposes a country or region's welfare change into market and non-market components. First, removing explicit subsidies on fossil fuels (where they exist), increases welfare on both dimensions. Market welfare increases as the subsidy removal reduces market distortions, narrowing the gap between bring producer and consumer prices of energy. As reduced subsidies lower fossil energy use, the non-market welfare effect is positive, too. Second, both components of welfare do not move in the same direction when applying Pigouvian pricing of local externalities, i.e. there is a trade-off between market and non-market welfare. Pigouvian pricing increases non-market welfare, but higher energy prices mean economic cost in terms of market-based consumption, implying a decrease in market welfare. By how much positive non-market effects outweigh negative market effects ultimately is an empirical question. We find a positive net effect for all countries, i.e. all countries fall above the 45° line. Countries with high marginal damages or high energy intensity of consumption (or both) experience particularly large benefits.

FISCAL REVENUE EFFECTS.—Figure 8 reports the fiscal revenues, expressed in % of consumption, which could be generated on an annual basis by local Pigouvian energy pricing, comprising both expenditures saved from removing explicit subsidies on fossil fuels and revenues collected from pricing local externalities. We find that fiscal revenues from a unilateral approach to get energy prices right would be substantial. On average, countries or regions would obtain revenues equal to 4.9% of consumption or billion $223 per year, ranging from 1.8–16.2% at the country or regional level. Removing explicit subsidies would, on average, only create additional fiscal income of 0.4% (billion $7) per year, whereas pricing local externalities would generate comparably large revenues. Pricing externalities related to local air pollution would, on average, yield fiscal revenues equal to 2.5% of consumption or billion $124 per year, and pricing non-pollutant externalities 2.0% of consumption or billion $91 per year.[14] Summing over all countries and regions, we estimate that the total fiscal revenues from local Pigouvian energy pricing would amount to 4.9% of global consumption or trillion $2.5 per year. Major EU countries (Germany, France, Italy) can also expect substantial inflows for the public budget from local Pigouvian pricing ranging from 2.1 to 2.9% (billion $26–59) while the rest of Europe may even collect amounts totaling 4.3% (billion $192).

LABOR TAX REDUCTION.— So far revenues from local Pigouvian energy pricing were forwarded to the households as per capita lump-sum payments. Here, we analyze how tax revenues could be used to lower other distortionary taxes, namely labor taxes. Table 4 presents the changes (in %) in welfare, utility from private consumption, local externalities (see (1)) and CO2 emissions if revenues from local Pigouvian pricing are used to reduce labor taxes as well as the differences (in p.p.)

[14]While pricing of non-pollutant externalities has relatively little impact on welfare (compared to pricing externalities from local air pollution), it is relatively more important for fiscal revenues. This is largely explained by the fact that the demand for transportation services, and hence oil used for transportation, is relatively price inelastic. Pricing non-pollutant externalities thus brings about small changes in non-market welfare, while the small changes in quantity implies that the Pigouvian tax in transportation is applied to a relatively inelastic tax base and a small tax evasion due to behavioral responses in equilibrium.

FIGURE 8. Annual tax revenues (in % of consumption) of unilateral fossil fuel subsidy removal and Pigouvian pricing of local externalities



compared to the case in which revenues are forwarded as per capita lump-sum payments to households.

First, as in the case of sole pricing, all countries and regions experience welfare gains in this policy scenario. Second, with a few exceptions, labor tax redcution brings greater welfare benefits than forwarding revenues as lump-sum payments. On average, welfare benefits are 0.16 percentage points higher. Particularly major EU countries Germany (0.28 p.p.) France (0.40) and Italy (0.24) may benefit from recycling revenues for labor tax reduction as well as the rest of Europe (0.36), all with above average welfare gains. Table 4 also reveals that utility from consumption as well as local externalities are both larger under labor tax reduction policies. In other words, the lower reductions in local externalities when recycling tax revenues for labor tax cuts are outweighted by attenuated adverse effects on private consumption yielding overall positive net welfare effects compared to lump-sum payments. Since higher externalities imply higher usage of fossil fuels, co-benefits in terms of reduced CO_2 emission are lower as well, by on average 0.4 p.p..

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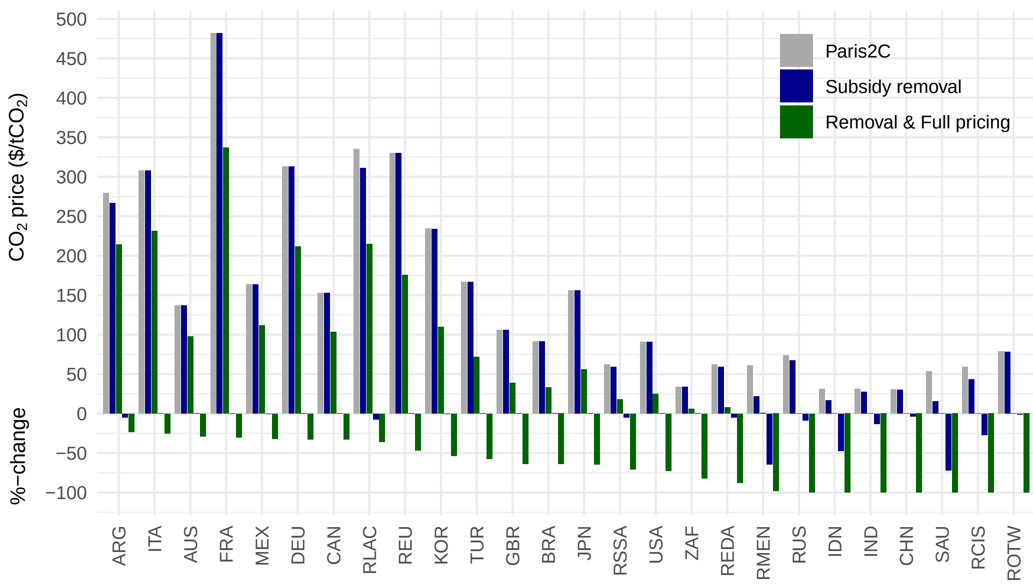
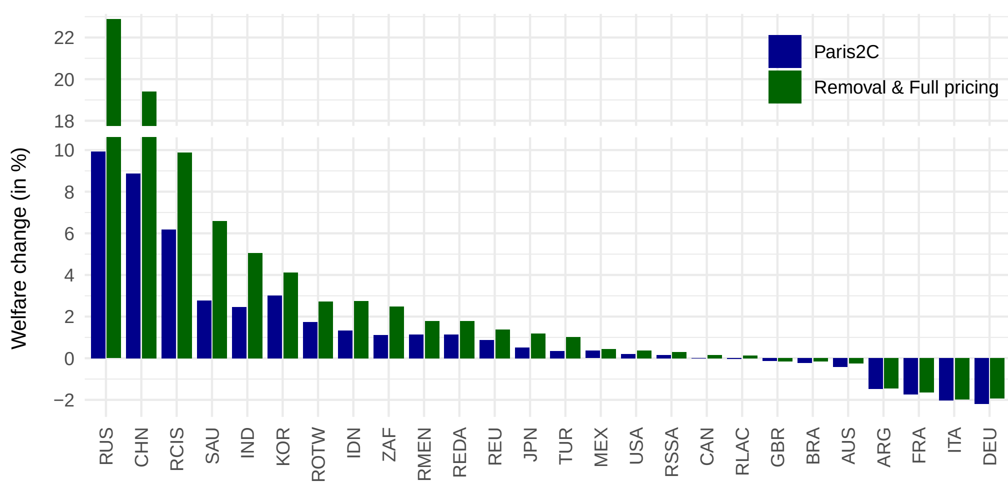
IMPLICATIONS FOR THE ECONOMIC COSTS OF CLIMATE TARGETS.—The case for unilateral local Pigouvian energy pricing may be reinforced if it reduces the need for further, costly carbon abatement measures that a country needs to take to meet its climate targets under the Paris agreement. We investigate this climate-related dimension 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 Paris climate target if local Pigouvian pricing is applied?

Figure 9, Panel (a), compares carbon prices required to achieve a country's or region's Paris climate target without and with local Pigouvian energy pricing. First, explicit subsidy removal applies only in about 40% of the regions, but would already reduce carbon prices in these regions by 10% on average. Second, subsidy

FIGURE 9. 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: "No reform" refers to achieving Paris targets with national carbon pricing only, i.e. without subsidy reform or additional pricing of local externalities. The y-axis shows the level of the CO_2 price π_r above and the respective percentage change below the zero line.

TABLE 4. Local Pigouvian energy pricing & Labor tax reduction

Region	Change (%, relative to "No reform")				Difference to lump-sum (p.p.)			
	Welfare	Consump.	Local Ext.	CO_2	Welfare	Consump.	Local Ext.	CO_2
ARG	0.31	-0.50	-0.50	-10.4	0.12	0.12	0.24	0.3
AUS	0.48	-0.51	-0.51	-14.0	0.05	0.06	0.22	0.2
BRA	0.18	-0.42	-0.42	-13.3	0.17	0.17	0.30	0.3
CAN	0.81	-0.59	-0.59	-14.0	0.14	0.15	0.37	0.3
CHN	19.53	-7.01	-7.01	-52.9	0.13	0.23	0.44	0.5
DEU	0.44	-0.92	-0.92	-25.6	0.28	0.28	0.34	0.4
FRA	0.45	-0.68	-0.68	-19.4	0.40	0.40	0.41	0.5
GBR	0.06	-0.59	-0.59	-14.7	0.11	0.11	0.29	0.3
IDN	2.74	0.06	0.06	-33.3	-0.01	-0.00	0.22	0.2
IND	4.97	-2.51	-2.51	-41.8	-0.08	0.03	0.62	0.6
ITA	0.06	-0.61	-0.61	-13.0	0.24	0.24	0.30	0.4
JPN	1.82	-1.43	-1.43	-21.5	0.37	0.37	0.44	0.5
KOR	4.80	-0.91	-0.91	-32.1	0.28	0.31	0.48	0.5
MEX	0.72	-0.30	-0.30	-14.5	0.01	0.02	0.26	0.3
RCIS	10.00	-1.72	-1.72	-36.0	0.12	0.19	0.49	0.8
REDA	1.76	-0.57	-0.57	-25.1	-0.02	-0.00	0.31	0.3
REU	2.68	-1.05	-1.05	-32.7	0.36	0.35	0.32	0.4
RLAC	1.32	-0.58	-0.58	-22.2	0.06	0.08	0.31	0.3
RMEN	1.81	0.17	0.17	-22.6	0.01	0.02	0.23	0.2
ROTW	2.83	-0.00	-0.00	-30.9	0.10	0.11	0.25	0.3
RSSA	0.33	-0.18	-0.18	-14.8	0.01	0.01	0.17	0.2
RUS	23.21	-4.66	-4.66	-34.7	0.32	0.39	0.53	1.0
SAU	6.45	-0.21	-0.21	-21.1	-0.15	-0.05	0.60	0.7
TUR	2.40	-2.95	-2.95	-27.0	0.42	0.45	0.62	0.7
USA	0.56	-0.47	-0.47	-23.8	0.12	0.13	0.27	0.3
ZAF	2.58	-0.99	-0.99	-23.3	0.09	0.14	0.61	0.6

Note: 'Change (%, relative to "No reform")' describes the change in the indicated macro parameter under local Pigouvian pricing combined with labor tax recycling relative to no policy taking place (i.e. neither local Pigouvian pricing nor labor tax reduction). 'Difference to lump-sum (p.p.)' is defined by the 'Change (%, relative to "No reform")' for local Pigouvian pricing combined with labor tax recycling minus the 'Change (%, relative to "No reform")' for local Pigouvian pricing combined with lump-sum recycling.

removal & full pricing of local externalities would bring about a substantial decrease in required carbon prices with, on average, a reduction of 76% (equivalent to a reduction of the average carbon price from \$55 to \$11 per ton of CO_2). Third, a striking result is that with local Pigovian energy pricing about 50% of countries and regions would already over-achieve their NDC target, implying that the required carbon price to meet the Paris climate target is zero (i.e., it is reduced by a 100%).

Figure 9, Panel (b), reports a country's or region's welfare change, including market and non-market effects, resulting from local Pigouvian energy pricing when combined with a climate policy based on the Paris targets. We find that achieving the climate target without removing explicit and implicit subsidies on fossil fuels yields welfare gains for most countries and regions. On average, welfare increases by 0.7%. While this finding is not the focus of this paper, it is consistent with the findings of 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). The novel insight is that most regions experience substantially higher welfare gains (or reduce welfare losses) if they partly use policies to price local externalities related to fossil fuels to achieve their climate targets. On average across all countries and regions, we estimate that the welfare gain increases by 3 percentage points or 429%. The reason is that $CO2_2$ 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.

Countries seeking to maximize welfare in light of these local externalities should therefore use energy pricing policies that appropriately reflect the local cost of using fossil fuels. Our analysis even suggests that some countries or regions may find climate policy redundant when local Pigouvian energy pricing is applied. In these cases, the carbon price drops to zero (see Figure 9, Panel (a)). These regions are strictly better off achieving reductions in fossil energy use through local Pigouvian pricing policies rather than implementing climate policy. This is particularly the case for Germany and other European countries, while Paris 2°C compatible carbon prices in France and Italy would be lowered by more than 50%.

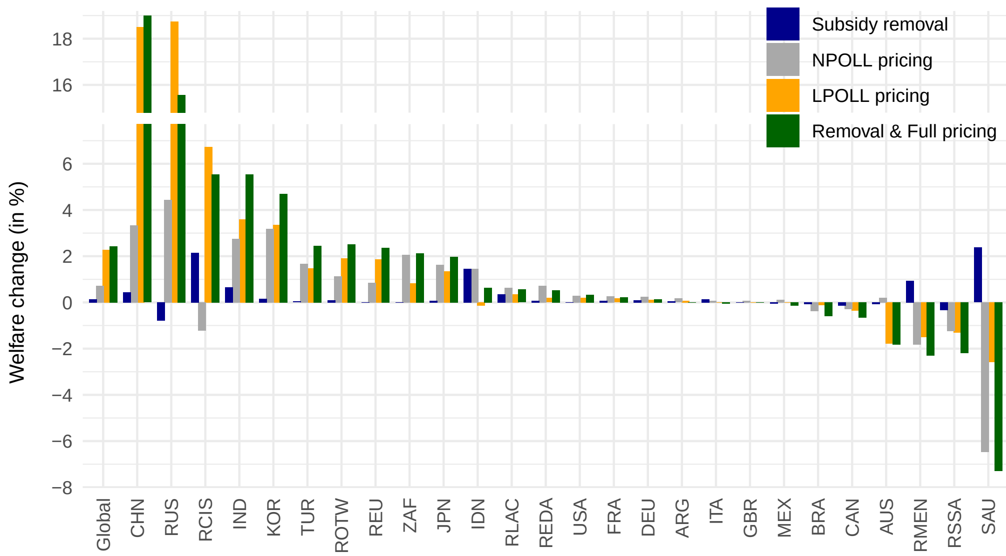
B. Foregone Welfare Gains of Today's Fossil-based Global Economy

Today's economies around the world are highly dependent on fossil fuels, the use of which entails significant costs due to adverse local effects that are not internalized in market decisions. We use our model to provide a quantitative estimate of the welfare gains foregone due to the unregulated use of fossil fuels in today's economies. Importantly, in deriving such an estimate, both the domestic and international market responses of economies to a comprehensive and globally enacted Pigouvian pricing of local externalities must be taken into account, as is featured by our model. A counterfactual with Pigouvian pricing in all countries and regions undoubtedly describes a hypothetical, if not utopian, world.

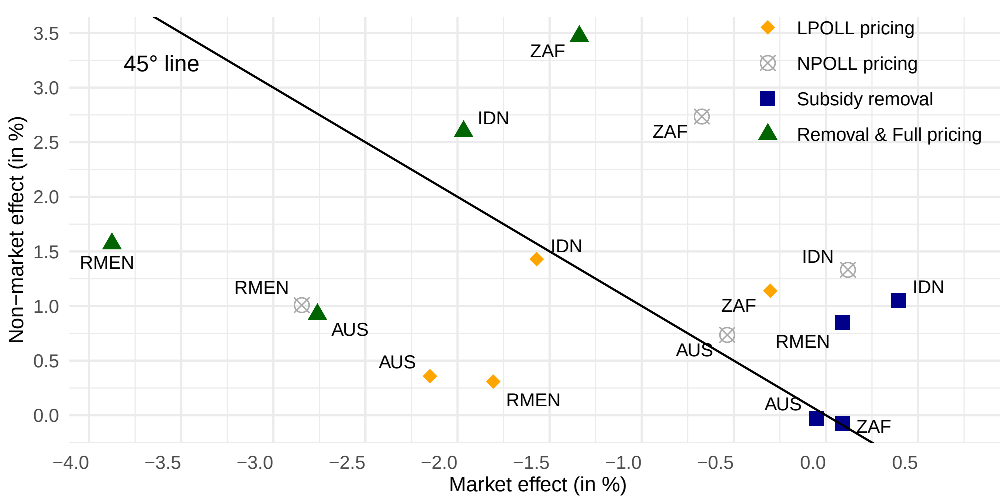
GLOBAL WELFARE EFFECTS.—Figure 10 reports the foregone welfare effects by region and at the global level; Panel (a) reports the total welfare changes which are decomposed in Panel (b) into market and non-market welfare effects. We estimate that the welfare cost from using fossil energy in an unregulated manner in today's global economy amounts to 2.4% of global consumption (Panel (a)). Just by pricing local externalities related to air pollution would reap more than 90% of these welfare gains, yielding a global welfare gain of 2.3%. Pricing non-pollutant externalities would bring about a global welfare gain of 0.7%. The effects from removing explicit subsidies are relatively small if measured at global scale, with a welfare gain of 0.1%. If tax revenues from local Pigouvian pricing were in addition used to reduce taxes on labor, welfare gains would even amount to 2.7%.

WELFARE EFFECTS BY COUNTRY AND REGION.—Welfare gains (losses) at the country or regional level are smaller (larger) under global joint as compared to unilateral implementation of local Pigouvian energy pricing (compare with Figure 6). If all regions adopt local Pigouvian pricing, fossil energy and energy-intensive goods imports become costlier. Unlike unilateral action, local energy pricing adopted globally reduces firms' and consumers' ability to substitute imported goods in response to higher domestic energy and energy-intensive goods prices. Interestingly, Europe would slighlty benefit from a joint global implementation, increasing countries welfare on average by 0.1 p.p. compared to the unilateral case.

FIGURE 10. Unrealized welfare effects of fossil fuel subsidy removal and pricing of local externalities at global scale



(a) Welfare change by region



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

Fossil energy exporters face welfare losses as global demand for fossil imports declines. Panel (b) of Figure 10 highlights these effects, with some regions falling below the 45° line (unlike the unilateral case in Figure 7, where all are above it). For oil exporters like RCIS, RMEN, and Saudi Arabia, local energy pricing for oil-related transport use has the largest welfare impact. However, these losses are mitigated or offset when subsidy removal and comprehensive pricing scenarios are considered, especially for RCIS. Similarly, coal exporters like Indonesia, Australia, and Canada face welfare losses as coal demand drops. In contrast, Russia and South Africa gain more from pricing their local pollutant externalities than they lose from reduced coal trade.

Our analysis highlights that local Pigouvian energy pricing is preferable for all countries and regions, even those negatively affected if it is adopted jointly at a global scale. While some countries face welfare losses from reduced fossil fuel export income, addressing domestic fossil fuel externalities is a dominant strategy that partially offsets these losses.

C. Climate Co-benefits of Local Pigouvian Energy Pricing

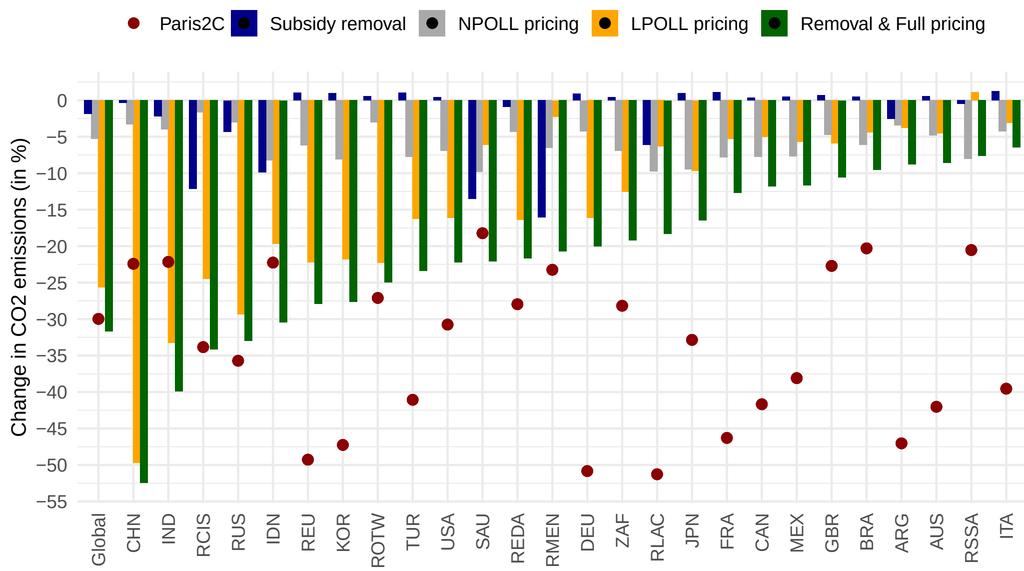
We finally examine the climate change mitigation benefits of local Pigouvian energy pricing if adopted by all countries and regions. While hypothetical, this counterfactual helps assess how far fossil energy pricing based on internalizing local externalities related to fossil fuel use, could advance global and national progress toward Paris Agreement climate goals. The guiding questions are: By how much would global carbon emissions be reduced by local Pigouvian energy pricing adopted at global scale? To what extent are national climate targets already being met? What are the implications for the welfare costs and carbon prices required to achieve the Paris targets?

Figure 11, Panel (a), compares global and regional CO_2 emission reductions at different levels of local Pigouvian energy prices with the climate targets set under the Paris Agreement. We estimate that global emissions would be reduced by 32% if all regions implemented comprehensive energy pricing reforms that include the removal of subsidies and full pricing of local externalities. A large part of this reduction is due to the pricing of local externalities related to air pollution (LPOLL), which alone leads to a 26% reduction in global CO_2 emissions. At a global level, this would already meet the required reduction in the context of development compatible with Paris 2°C.

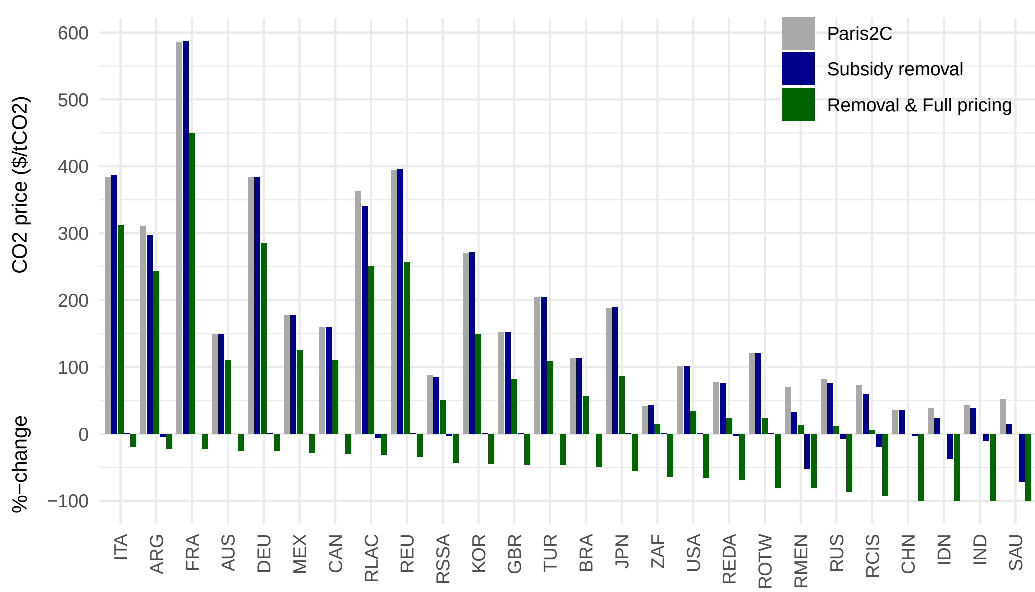
Removing explicit fossil fuel subsidies globally would only minorly contribute to achieving the Paris agreement, reducing CO_2 emissions by only 2%.[15] Internalizing non-pollutant externalities associated with oil use (mainly in transportation), would reduce global CO_2 emissions by 5%. There are large regional differences in the achievement of the national Paris targets, which could be achieved through local Pigouvian energy pricing. About 40% of the countries or regions, includ-

[15]Our estimate for global emissions impact of removing explicit fossil subsidies is in line with comparable estimates from the literature, which finds reductions of about 1–4% (Jewell et al., 2018; Chepeliev and van der Mensbrugghe, 2020; Arzaghi and Squalli, 2023).

FIGURE 11. 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: "No reform" refers to achieving Paris targets with national carbon pricing only, i.e. without subsidy reform or additional pricing of local externalities. The y-axis shows the level of the CO_2 price π_r above and the respective percentage change below the zero line.

ing China, Russia and Rest of Europe would already reach their Paris target. For most of these countries, pricing local air pollution externalities significantly reduces CO_2 emissions. However, for nations with high explicit fossil energy subsidies, like Saudi Arabia and MENA countries, subsidy removal is key to meeting Paris targets through energy pricing reform. Other industrialized and energy-importing countries like Germany, US, France, Japan and United Kingdom would already achieve a substantial fraction (more than 50%) of their Paris target through local Pigouvian energy pricing.

Figure 11, 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 Paris target resulting from local Pigouvian energy pricing. On average across countries, the carbon price to achieve Paris targets is reduced by 79% and drops by 100% 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.

VIII. Conclusion

The global public good nature of climate change mitigation and the resulting free-rider problem require a restructuring of the incentives for countries to price fossil energy consumption. This paper has examined the regional and global efficiency, distributional, and fiscal effects from price-based climate policy based on removing explicit and implicit fossil fuel subsidies, the latter entailing Pigouvian pricing of major local externalities. We have developed a multi-sector multi-region equilibrium model that incorporates granular data on fossil fuel subsidies, local external costs, and international market responses, using national income data and bilateral international flows to capture global supply chains and sector-specific impacts. We find that removing explicit subsidies yields small welfare gains, while local Pigouvian energy pricing generates average gains of 3.9%, with country-level gains ranging from 5-23%. Pricing externalities from local air pollution captures 75% of these benefits. Fiscal revenues from removing both explicit and implicit subsidies amount to 4.9% of global consumption, or USD 2.5 trillion per year. Unilateral subsidy removal lowers the shadow cost of carbon by 76%, helping about 50% of countries, including China, Russia and Rest of Europe surpass their Paris targets, while generating significant welfare gains. Unrealized welfare gains from underpricing fossil energy total 2.4% of global consumption, with 90% due to local air pollution. Our analysis thus points to strong unilateral incentives for countries to eliminate explicit and implicit fossil fuel subsidies while contributing to the global public good of climate change mitigation.

While global adoption may be seen as a hypothetical, politically feasible upper bound, in terms of local benefits we likely even (drastically) underestimate potential welfare gains. Particularly estimates of local pollutant pricing are conservative as other non-mortality related adverse effects of pollution (e.g. on labor productivity) are not considered.[16]

Other general limitations of our analysis relate to data uncertainty and model assumptions. While we exploit rich granular data on local marginal damages, data collected for such a variety of countries and sectors typically underlie measurement error and comparison requires making further assumptions. In the absence of confidence intervals for damage estimates in the IMF data set, which is currently the sole available source for our purposes, we are unable to quantify the related uncertainty. In addition, our explicit subsidy data are limited to consumer support. Since subsidies for producers are considered to be comparatively small, we do not expect that including them would significantly change our results. Furthermore, our model is of static nature and does not account for the potential adoption of (green) technologies, such as hydrogen, which are currently unexploited and therefore not reflected in the economic data.

Despite of the apparent local and global benefits of reforming energy prices, one may wonder why we do not see more reform efforts globally. While in recent years some countries have indeed implemented energy pricing reforms (Coady, Parry and Shang, 2018), this study reveals a large, still untapped potential for further action. There may be many possible political economy related reasons why this potential is not being exploited (see e.g. Inchauste and Victor (2017); Mahdavi, Martinez-Alvarez and Ross (2022); Droste, Chatterton and Skovgaard (2024)). Since it is not the focus of this study, we can not give a definite answer but some detected facts may be of relevance. First, welfare improvements are achieved by reducing damages from local externalities at the expense of utility from private consumption. The former presents to greater extent intangible, counterfactual, and abstract non-market effects (e.g. , decreased mortality risk, non-experienced accident or congestion) that may occur in the distant future. As a result, the perception and communicability of the benefits of a far-reaching energy price reform in political discourse can be severely limited. Second, we have seen that some countries and regions face negative welfare effects under global adoption due to decreased fossil fuel demand. Accordingly, these regions will not lobby for a reform at the global level even if they acknowledge an energy pricing reform at home. Indeed, a more systematic investigation of this political economy issue may be an interesting path forward for future research.

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[16]See e.g. Williams (2002) for a theoretical exploration in a static GE model and Bretschger and Komarov (2024) for a quantitative assessment of pollution related health effects on economic growth. The latter estimate that explicitly incorporating health damages on productivity reduces the optimal rate of fossil fuel resource extraction from 44% to 1% of the stock.

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Appendix A: Additional Figures and Tables

Table A1. Descriptive statistics on fossil fuel subsidies and costs of local externalities by fuel (in % of benchmark consumption).

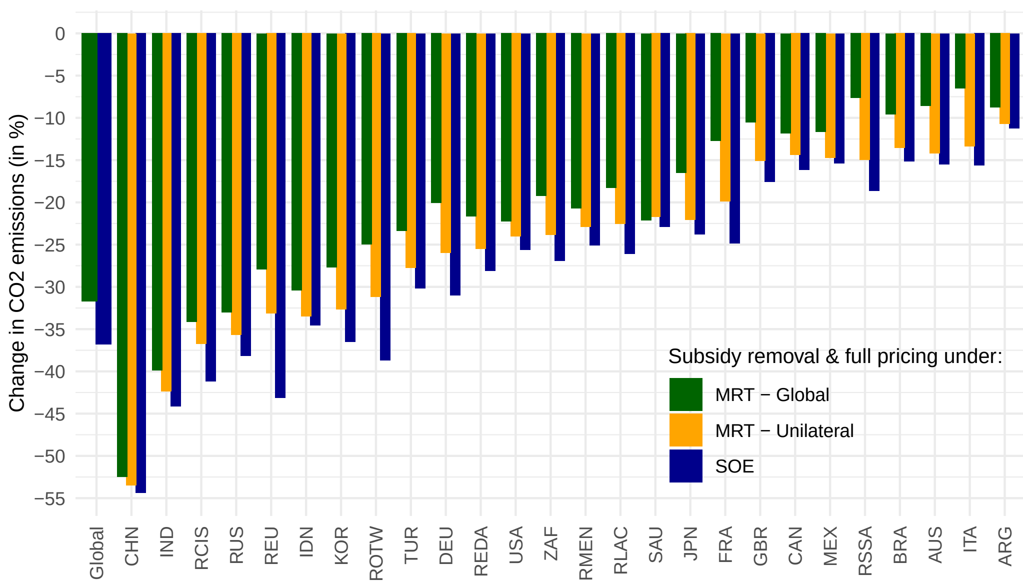
Region	Fossil fuel subsidies			Local externalities		
	Refined oil	Natural gas	Coal	Refined oil	Natural gas	Coal
ARG	0.40	0.10	0.00	2.70	0.10	0.10
AUS	—	—	—	3.00	0.00	0.20
BRA	—	—	—	2.60	0.00	0.10
CAN	—	—	—	4.20	0.10	0.10
CHN	0.30	—	—	6.10	0.10	25.90
DEU	—	—	—	3.00	0.10	1.10
FRA	—	—	—	3.50	0.10	0.30
GBR	—	—	—	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 A2. 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	1969.8
AUS	0.3	0.4	-1.8	-0.1	31.3	2.1	116.2
BRA	-0.2	0.0	-0.6	-0.2	1790.0	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	2987.9
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

Note: "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.

FIGURE A1. Impacts of fossil fuel subsidy removal on CO_2 emissions under alternative international trade closure



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