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The consequences of unilateral withdrawals from the Paris Agreement

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KIEL WORKING PAPER

The Consequences of Unilateral Withdrawals from the Paris Agreement



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Mario Larch and Joschka Wanner

ABSTRACT

The Consequences of Unilateral Withdrawals from the Paris Agreement*

Mario Larch and Joschka Wanner

International cooperation is at the core of multilateral climate policy. How is its effectiveness harmed by individual countries dropping out of the global mitigation effort? We develop a multisector structural trade model with emissions from production and a constant elasticity of fossil fuel supply function to simulate the consequences of unilateral withdrawals from the Paris Agreement. Taking into account both direct and leakage effects, we find that a US withdrawal would eliminate more than a third of the world emissions reduction (31.8% direct effect and 6.4% leakage effect), while a potential Chinese withdrawal lowers the world emission reduction by 24.1% (11.9% direct effect and 12.2% leakage effect). The substantial leakage is primarily driven by technique effects induced by falling international fossil fuel prices.

Keywords: Climate change; International trade; Carbon leakage; Fossil fuel supply

JEL classification: F14; F18; Q56

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1 Introduction

The coming into force of [the] Paris Agreement has ushered in a new dawn for global cooperation on climate change.

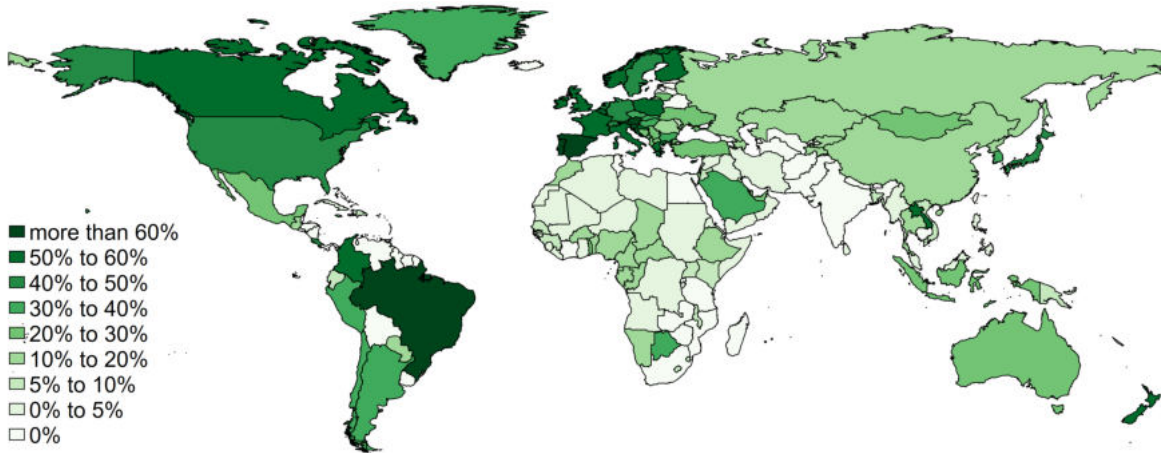
(Then UN Secretary General Ban Ki-Moon, November 15th, 2016)

[I]n order to fulfill my solemn duty to protect America and its citizens, the United States will withdraw from the Paris Climate Accord.

(Then US President Donald Trump, June 1st, 2017)

In December 2015, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) reached a joint agreement to combat climate change. With its 195 signing countries, the Paris Agreement constitutes a truly global consensus to take appropriate measures to keep global warming well below two degrees Celsius. One centerpiece of the agreement are the Nationally Determined Contributions (NDCs) in which every country specifies an individual greenhouse gas (GHG) emission reduction target. Figure 1 shows the different national reduction targets, standardized to reductions compared to a business as usual (BAU) scenario in 2030, to make the targets comparable.¹

Figure 1: Emission Reduction Targets in the Paris Agreement



Notes: This figure shows the emission reduction targets specified in the individual countries' NDCs (or, where no NDCs are available, the Intended NDCs). To make the targets comparable, all are given as reductions below the business as usual emission path in 2030. National targets aggregate to a 25.4% global reduction compared to a BAU emission path. For details on the targets and their standardization, see Section 3.

The large heterogeneity in ambition of the targets becomes evident at first sight. While some Asian and African countries merely commit to not *increase* their emissions beyond the BAU path and some have rather mild targets (like the 11.3% of China), large parts of Europe and the Americas formulate strong targets that in some cases lower their emission by more than half. What is more crucial though and most likely explains at least part of the enthusiasm expressed for example in the first opening

¹Details on the standardization are given in Section 3.2.

quote by the former UN Secretary General Ban Ki-Moon, is the fact that *every country* has a target. The subglobal coverage of the Paris Agreement’s most prominent predecessor, the Kyoto Protocol, has severely harmed its effectiveness due to leakage effects (see e.g. Aichele and Felbermayr, 2012, 2015). Carbon leakage refers to the phenomenon that climate policies undertaken in some countries can lead to *increased* emissions in other places where no such policies are undertaken due to (i) production shifts of emission-intensive goods towards the un-(or less) regulated countries and (ii) falling fossil fuel prices on the world market that incentivize a more fossil fuel-intensive production (see e.g. Felder and Rutherford, 1993). The underlying free-riding problem of international climate policy is analyzed by Nordhaus (2015).

As the second opening quote by former US President Donald Trump clearly shows, the hope of achieving the world emission reduction that would result from adding up all national targets may be overly optimistic. Following through on the announcement, the United States officially left the Agreement in November 2020.² Even though the United States is rejoining under Trump’s successor Joe Biden, the episodes clearly demonstrates the fragility of the global consensus. Countries that decide not to commit to their emission targets harm the effectiveness of the Paris Agreement in two ways. First and most obviously, the sum of the national targets is lowered if some countries drop their target. Second and potentially just as important, withdrawals can induce carbon leakage that lowers the achieved world reduction below the remaining sum of national targets. The first effect can easily be calculated by combining the national targets shown in Figure 1 with data on the national emission levels and is shown in Figure 2 and (for the five countries with the strongest effects) in Table 1.

Table 1: Top Five Direct Reduction Losses

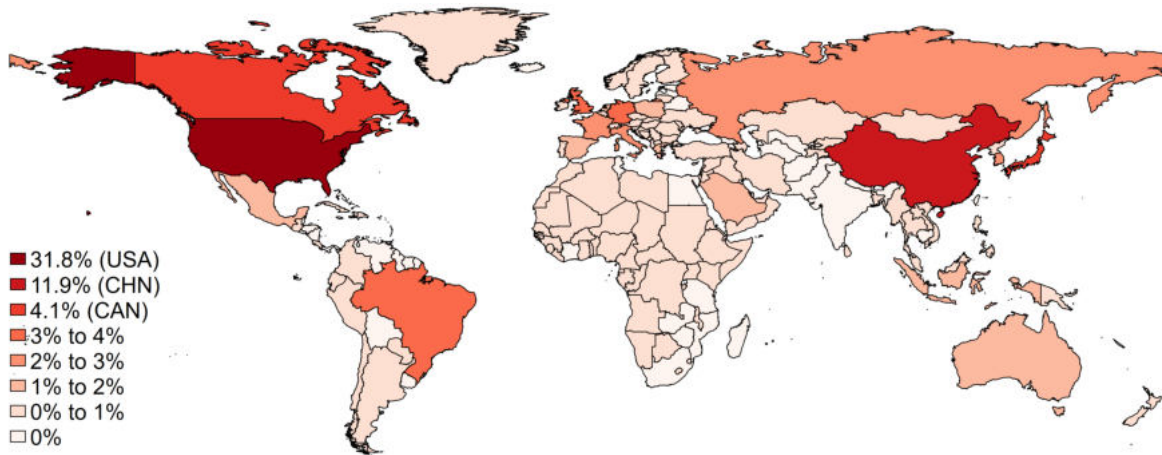
Withdrawing country	USA	CHN	JPN	CAN	BRA
World reduction lost (direct effect)	31.8%	11.9%	5.6%	4.1%	3.8%

China (7998 Mt CO₂)³ and the United States (5156 Mt CO₂) are by far the largest emitters. Unsurprisingly, their withdrawals would directly lower the world emission reduction comparatively strongly. Even though the US comes second in terms of emissions, its combination of large emissions with a rather ambitious NDC reduction target (47%) makes the direct effect of a US withdrawal the by far strongest of all countries: almost a third of the global reduction would be lost due to the absence of the US target. China (11.9% world reduction loss) comes in second, while Japan (5.6%) has the third strongest effect. These two countries’ strong effects come about in very different ways: very

²Additionally, a small number of other signing countries of the agreement (Iran being the largest among them in terms of carbon emissions) have not yet moved on to ratification.

³The emission data used here refer to the year 2014 and capture only carbon and no other GHG emissions. For details, see Section 3.

Figure 2: World Reduction Lost by Withdrawn Commitments (Direct Effect Only)



Notes: This figure shows for every country in turn, which share of the world emission reduction due to the Paris Agreement would be lost if the respective country withdraws from the agreement and its target specified in the NDC is hence no longer part of the global reduction. Endogenous adjustments of withdrawing country to other countries' climate policies with potentially resulting emission *increases* in the withdrawing country beyond the BAU path are not taken into account at this point.

large emissions and a mild target in one case (China) and much lower emissions (about one seventh of the Chinese level) and an ambitious target (41%) in the other case (Japan). Besides these three countries, a group of European countries, as well as two more large developed countries (Canada and South Korea) combine high emission levels and strong targets to notable direct reduction losses in case of withdrawal of two to four percent. Brazil makes the top five despite being only number eleven in terms of emissions, due to a very ambitious reduction pledge (65%). Russia, on the other hand, is the world's fourth largest emitter but comes only in eighth place in terms of the direct reduction loss due to a comparably mild reduction target of 15%. All African and most Asian countries have either sufficiently low emissions or very small targets (or both) so that the loss of their target would not alter the achieved world reduction conceivably.

One prominent example illustrates the limitations of considering only the direct effect of removing a withdrawing country's target particularly well: India. India's target implies only a commitment to *not increase* emissions above the BAU path. Removing such a "zero target" does not change the sum of targets and hence, these countries' withdrawals are depicted with a zero effect in Figure 2. But indeed, an Indian decision to withdraw from the Paris Agreement and not take any climate policy measures may induce carbon leakage and therefore harm the achieved global emission reduction indirectly. Such leakage effects will not only introduce effects for countries with zero targets, but they will also amplify the effects of all other countries' withdrawals.

Different from the direct effects, leakage effects (and hence the total effects) of unilateral with-

drawals cannot be simply calculated, but have to be solved using a multi-country general equilibrium framework. The most common approach to investigate the global effects of different trade and climate policies is the use of computable general equilibrium (CGE) models (see e.g. Böhringer, Balistreri, and Rutherford, 2012, for an overview of various prominent CGE models). A recent strand of literature (Egger and Nigai, 2015; Larch and Wanner, 2017; Larch, Löning, and Wanner, 2018; Shapiro, 2016, 2021; Shapiro and Walker, 2018; Caron and Fally, 2020; Farrokhi and Lashkaripour, 2021) incorporates environmental components into structural gravity models as an alternative approach.⁴ Gravity models are the workhorse models in the empirical international trade literature. Just as CGE models, they can be used to conduct ex-ante analyzes of different policy scenarios. Compared to typical CGE models, they tend to sacrifice some detail in the model structure in favor of higher analytical tractability and direct estimation of key model parameters.

Given gravity’s great success in predicting trade flows (see e.g. Head and Mayer, 2014; Costinot and Rodríguez-Clare, 2014, for surveys on gravity models and their performance), it is likely to capture well leakage that occurs via production shifts and international trade. The main model of Larch and Wanner (2017), as well as the models by Shapiro (2016), Shapiro and Walker (2018), and Farrokhi and Lashkaripour (2021) exclusively focus on this leakage channel. In this paper, we extend the model of Larch and Wanner (2017) by considering fossil fuel resources that are internationally traded and supplied according to a constant elasticity of fossil fuel supply function as proposed in the CGE context by Boeters and Bollen (2012). The resulting extended gravity model will capture leakage effects via international trade and via the international fossil fuel market and hence allow a quantification of the total emission reduction losses associated with unilateral withdrawals from the Paris Agreement. At the same time, the model structure remains tractable enough to allow an analytical and quantitative decomposition of the national emission changes into scale, composition, and technique effects as is often done in the theoretical and empirical literature on trade and the environment (see e.g. Grossman and Krueger, 1993; Copeland and Taylor, 1994, 2003). Such a decomposition can generate important insights about the channels via which international climate policies are effective.

Our analysis of the effects of unilateral withdrawals complements other studies that investigate the Paris Agreement and its implications. For example, Glanemann, Willner, and Levermann (2020) investigate whether the Paris goal of keeping global warming well below two degrees is economically sensible: it is because avoided damages outweigh mitigation costs. Rogelj et al. (2016) analyze whether the individual national targets are sufficient to jointly achieve the two (or even 1.5) degree Celsius

⁴Pothen and Hübler (2018) develop a hybrid model, combining an Eaton and Kortum (2002)-type gravity trade structure with a CGE model production structure.

target: they are not. Aldy and Pizer (2016), Aldy, Pizer, and Akimoto (2017), and Iyer et al. (2018) aim to make the different NDCs comparable in their implied required mitigation efforts of the different countries. Rose et al. (2018) investigate one particular way for efficiently achieving the reduction pledges, namely by linking different emissions trading schemes. Nong and Siriwardana (2018) analyze the consequences of a US withdrawal on the US economy, finding besides others a significant drop in energy prices. Böhringer and Rutherford (2017) and Winchester (2018) show that the introduction of carbon tariffs is not a credible threat towards the US to try to keep them in the agreement. Kemp (2017) considers measures that can be taken to reduce the damage to the effectiveness of the agreement due to a US withdrawal, e.g. by incorporating cooperation with US states. We contribute to the literature by quantifying the harm done by countries withdrawing from the Paris Agreement taking into account both direct effects and emission shifts (leakage) resulting from general equilibrium adjustments of supply and demand of goods and fossil fuels.

The rest of this paper proceeds as follows. Section 2 develops our extended structural gravity model, shows how counterfactual analyzes can be performed in this framework and derives the emission change decomposition. In Section 3, the data sources and descriptive statistics are presented, as well as the gravity estimation procedure. We discuss the results of simulating the unilateral withdrawal for every country in Section 4. In Section 5, we derive a model extension with multiple fossil fuels of varying carbon intensities, demonstrate how this extension leads to a fourth, substitution, effect on emissions, and rerun the simulations using the extended model. Section 6 concludes.

2 Model

In this section, we develop an extended structural gravity model including a non-tradable and multiple tradable sectors, a multi-factor production function including an energy input, energy production including an internationally tradable fossil fuel resource, a constant elasticity of fossil fuel supply (CEFS) function following Boeters and Bollen (2012), as well as emissions associated to the fossil fuel usage. The model builds on the framework by Larch and Wanner (2017), but importantly deviates by (i) modeling the energy-market leakage channel using a CEFS function⁵, (ii) linking emissions directly to fossil fuel use rather than to general energy use, and (iii) explicitly including a carbon tax which countries can use to achieve emission reduction targets.

⁵The base model of Larch and Wanner (2017) only features the trade leakage channel, while the small model extension presented in their work relies on an energy resource in fixed supply.

2.1 Demand

Consumers in country $j \in \mathcal{N}$ (where \mathcal{N} denotes the set of all countries in the world) obtain utility according to the following utility function:

$$U^j = (U_S^j)^{\gamma_S^j} \left[\prod_{l \in \mathcal{L}} (U_l^j)^{\gamma_l^j} \right] \left[\frac{1}{1 + \left(\frac{1}{\mu^j} \sum_{i \in \mathcal{N}} R^i \right)^2} \right], \quad (1)$$

with

$$U_l^j = \left[\sum_{i \in \mathcal{N}} (\beta_l^i)^{\frac{1-\sigma_l}{\sigma_l}} (q_l^{ij})^{\frac{\sigma_l-1}{\sigma_l}} \right]^{\frac{\sigma_l}{\sigma_l-1}}, \quad (2)$$

where subscript S denotes the non-tradable sector, $l \in \mathcal{L}$ is one of the tradable sectors (with \mathcal{L} being the set of all tradable sectors), γ_l^j represents the expenditure share of sector l in country j , μ^j is a parameter that captures j 's disutility from global carbon emissions, R^i is country i 's fossil fuel use which is proportional to its emissions, β_l^i represents the utility parameter for tradable goods, q_l^{ij} is the amount of good l from country i consumed in country j , and σ_l stands for the sectoral elasticity of substitution. Equations (1) and (2) hence combine linear utility from non-tradable good consumption and CES utility from tradable goods consumption in an upper-tier Cobb-Douglas utility function (implying constant sectoral expenditure shares), as well as disutility from global emissions in the functional form chosen by Shapiro (2016) to ensure almost constant social costs of carbon around the baseline emission level.

Carbon emissions are treated as a pure externality (and are therefore not taken into account in the consumption decisions). Demand for non-tradable goods is then simply given by the corresponding expenditure \mathfrak{X}_S^j divided by the non-tradable good price ($q_S^j = \mathfrak{X}_S^j / p_S^j$). Demand for tradable goods l from i in j follows from CES utility as:

$$q_l^{ij} = \left(\frac{\beta_l^i p_l^{ij}}{P_l^j} \right)^{-\sigma_l} \left(\frac{\beta_l^i \mathfrak{X}_l^j}{P_l^j} \right), \quad (3)$$

where p_l^{ij} is the price including trade costs from i to j and P_l^j is the sectoral price index in j , given by:

$$P_l^j = \left[\sum_{i \in \mathcal{N}} (\beta_l^i p_l^{ij})^{1-\sigma_l} \right]^{\frac{1}{1-\sigma_l}}. \quad (4)$$

2.2 Supply

Each country produces a non-tradable good S , as well as a differentiated variety of each of $l \in \mathcal{L}$ tradable goods according to the following Cobb-Douglas production functions:

$$q_S^i = A_S^i (E_S^i)^{\alpha_{SE}^i} \prod_{f \in \mathcal{F}} (V_{Sf}^i)^{\alpha_{Sf}^i}, \quad (5)$$

$$q_l^i = A_l^i (E_l^i)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} (V_{lf}^i)^{\alpha_{lf}^i}, \quad (6)$$

where A_S^i and A_l^i are sector- and country-specific productivity parameters, α_{SE}^i , α_{lE}^i , α_{Sf}^i , and α_{lf}^i denote production cost shares, and V_{Sf}^i and V_{lf}^i the usages of a production factor $f \in \mathcal{F}$. Countries are endowed with a fixed factor supply V_f^i and factors are mobile across sectors, but internationally immobile. E_S^i and E_l^i denote the energy inputs in producing non-tradable and tradable goods, respectively. Different from the other production factors, countries are not endowed with a fixed energy supply, but the energy inputs have to be produced themselves according to the following Cobb-Douglas production function:

$$E^i = A_E^i (R^i)^{\xi_R^i} \prod_{f \in \mathcal{F}} (V_{Ef}^i)^{\xi_f^i}, \quad (7)$$

where ξ_R^i and ξ_f^i denote the input cost shares and R^i is the usage of a freely internationally tradable fossil fuel resource. National factor markets are assumed to clear, i.e. $V_f^i = V_{Sf}^i + \sum_{l \in \mathcal{L}} V_{lf}^i + V_{Ef}^i$, determining the factor prices v_f^i .

Countries can charge a national carbon tax λ^i on the use of fossil fuels to fulfill specific emission reduction targets and the fossil fuel price r is determined on the world market by global market clearing:

$$r = \frac{1}{R^W} \sum_{i \in \mathcal{N}} \left(\frac{1}{1 + \lambda^i} \right) \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i \right), \quad (8)$$

where $Y_S^i = q_S^i p_S^i$ and $Y_l^i = q_l^i p_l^i$ are the sectoral values of production. Following Boeters and Bollen (2012), a change in the fossil fuel price is translated into a change in the global supply of the fossil fuel with a constant elasticity of fossil fuel supply function:

$$\widehat{R^W} = \left(\frac{\widehat{r}}{\widehat{P}} \right)^\eta, \quad (9)$$

where η denotes the supply elasticity and the hat notation (introduced into the structural gravity literature by Dekle, Eaton, and Kortum, 2007, 2008) indicates the change of the respective variables,

i.e. $\widehat{R^W} = \frac{R^{W'}}{R^W}$ and $\widehat{r} = \frac{r'}{r}$, where the prime indicates a counterfactual value in response to a policy shock and values without a prime correspond to the baseline equilibrium. The total fossil fuel supply R^W stems from the different countries according to their varying fossil fuel endowment shares ω^i (with $\sum_{i \in \mathcal{N}} \omega^i = 1$). $\widehat{P} \equiv \prod_{i \in \mathcal{N}} (\widehat{P}^i)^{\omega^i}$ denotes the change of a global price index and hence translates the nominal resource prices change \widehat{r} into a real price change.

A change in the fossil fuel world market price further leads to an adjusted national energy price:

$$\widehat{e}^i = \left((1 + \lambda^i) \widehat{r} \right)^{\xi_R^i} \prod_{f \in \mathcal{F}} \left[\frac{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^{i'} + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^{i'}}{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^i} \right]^{\xi_f^i}. \quad (10)$$

Note that the adjustment of the energy price in response to a policy shock further depends on the endogenously adjusted, counterfactual production values. Subsection 2.5 will lay out the full system of equations that can—for a given counterfactual policy shock—be solved for the values of a sufficient set of endogenous variables from which all variables of interest can then be obtained.

2.3 Income

Countries generate income from (i) the expenditure on their national production factors, (ii) their share of the global supply of the fossil fuel, and (iii) the carbon tax charged on its fossil fuel use:

$$Y^i = \sum_{f \in \mathcal{F}} \left[(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^i \right] + \omega^i \sum_{j \in \mathcal{N}} \left(\frac{1}{1 + \lambda^j} \right) \xi_R^j \left(\alpha_{SE}^j Y_S^j + \sum_{l \in \mathcal{L}} \alpha_{lE}^j Y_l^j \right) + \left(\frac{\lambda^i}{1 + \lambda^i} \right) \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i \right). \quad (11)$$

2.4 Trade Flows

Introducing iceberg trade costs T_l^{ij} (with $T_l^{ij} = T_l^{ji} \geq 1$ and $T_l^{ii} = 1$) and defining sectoral scaled equilibrium prices as $\psi_l^i \equiv (\beta_l^i p_l^i)^{1-\sigma_i}$, the exports of country i to country j in sector l can be obtained from the bilateral demand given in Equation (3) as:

$$X_l^{ij} = \psi_l^i \left(\frac{T_l^{ij}}{P_l^j} \right)^{1-\sigma_i} \mathfrak{X}_l^j. \quad (12)$$

This gravity equation links bilateral trade flows to bilateral trade costs, the importer's market size and overall openness (captured by the price index which is equivalent to Anderson and van Wincoop (2003)'s inward multilateral resistance), as well as the overall exporting capability of country j (summarized by ψ_l^j which implicitly captures the exporter's size in terms of production and its outward multilateral

resistance).

Assuming balanced trade and market clearing, as well as using the sectoral price index given by Equation (4), from Equation (12) we can obtain an expression which links the sectoral production to the international trade cost matrix:

$$Y_l^i = \psi_l^i \sum_{j=1}^N \frac{(T_l^{ij})^{1-\sigma_l}}{\sum_{k=1}^N \psi_l^k (T_l^{kj})^{1-\sigma_l}} \gamma_l^j Y^j. \quad (13)$$

2.5 Comparative Statics

Equation (8) for the world market price of fossil fuels, Equation (9) depicting the constant elasticity of fossil fuel supply function, Equation (10) that captures the response in energy prices, Equation (11) which describes total national income, and Equation (13) linking sectoral production values and scaled equilibrium prices to the trade cost matrix (or the counterfactual equilibrium counterparts of these equations) describe a system of equations that can almost be solved for a given policy shock. Cost minimization in production allows to derive the second last necessary equation which captures the change in factory-gate prices (or equivalently in scaled equilibrium prices):

$$\left(\widehat{\psi}_l^i\right)^{\frac{1}{\sigma_l-1}} = (\widehat{e}^i)^{\alpha_{iE}} \prod_{f \in \mathcal{F}} \left(\frac{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{m \in \mathcal{L}} (\alpha_{mf}^i + \xi_f^i \alpha_{mE}^i) Y_m^i}{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^{i'} + \sum_{m \in \mathcal{L}} (\alpha_{mf}^i + \xi_f^i \alpha_{mE}^i) Y_m^{i'}} \right)^{\alpha_{if}}. \quad (14)$$

The last equation needed to solve the model for the counterfactual equilibrium stems from the specific policy scenario under investigation. We will run different scenarios in all of which all countries around the world will fulfill the emission reduction targets specified in their NDCs, except for one country that decides to withdraw from the agreement. We can link this scenario to the choice of the carbon tax λ^i in the model. Denoting the set of committed (or cooperating) countries by *cop*, the country that is not part of the agreement chooses a zero carbon tax, while all other countries choose their carbon tax exactly at the required level to ensure that their realized emissions are equal to their targeted emission level (denoted by $\overline{R}^{i'}$)⁶:

$$\lambda^i = \begin{cases} 0 & \text{if } i \notin \text{cop}, \\ \frac{\xi_R^i (\alpha_{SE}^i Y_S^{i'} + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^{i'})}{\overline{R}^{i'}} - 1 & \text{if } i \in \text{cop}. \end{cases} \quad (15)$$

⁶Note that we treat the targeted emission level $\overline{R}^{i'}$ as exogenously given. This is in contrast to two important recent contributions in the trade and environment literature by Farrokhi and Lashkaripour (2021) and Kortum and Weisbach (2021) that both consider *optimal* climate policies in an international setting. Kortum and Weisbach (2021), however, consider a two-country setting and Farrokhi and Lashkaripour (2021) abstract, as previously mentioned, from the energy market leakage channel, while our model brings together a multi-country setting and a consideration of both key leakage channels.

2.6 Decomposition of Emission Changes

As emissions are proportional to a country's fossil fuel use, emissions in country i can be written as:

$$R^i = \frac{\xi_R^i (\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i)}{(1 + \lambda^i)r} = \xi_R^i \bar{\alpha}_E^i \frac{\tilde{Y}^i}{P^i} \left(\frac{r^i}{P^i} \right)^{-1}, \quad (16)$$

where $\tilde{Y}^i \equiv Y_S^i + \sum_{l \in \mathcal{L}} Y_l^i$ denotes total (nominal) production, $\bar{\alpha}_E^i \equiv \alpha_{SE}^i \frac{Y_S^i}{\tilde{Y}^i} + \sum_{l \in \mathcal{L}} \alpha_{lE}^i \frac{Y_l^i}{\tilde{Y}^i}$ is the production-share-weighted average energy cost share, and $r^i \equiv (1 + \lambda^i)r$ is the national price for fossil fuels (including the carbon tax). Intuitively, the level of emissions in a country depends on (i) how much is spend for energy inputs in production, (ii) which share of the energy input expenditure is paid for fossil fuel inputs in energy production, and (iii) how expensive fossil fuels are (both in terms of the world market price and the national carbon tax).

Following Grossman and Krueger (1993) and Copeland and Taylor (1994) (as well as Larch and Wanner, 2017, in a structural gravity context), the change in emissions can then be decomposed into three parts:

$$dR^i \approx \underbrace{\frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} d(\tilde{Y}^i/P^i)}_{\text{scale effect}} + \underbrace{\frac{\partial R^i}{\partial \bar{\alpha}_E^i} d\bar{\alpha}_E^i}_{\text{composition effect}} + \underbrace{\frac{\partial R^i}{\partial(r^i/P^i)} d(r^i/P^i)}_{\text{technique effect}}.$$

Scale Effect. A country's fossil fuel use (and hence emissions) increases proportionally with the size of the economy (measured as the real value of production):

$$\frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} = \frac{\xi_R^i \bar{\alpha}_E^i}{(1 + \lambda^i)r/P^i} > 0 \quad \text{and} \quad \frac{\partial R^i}{\partial(\tilde{Y}^i/P^i)} \frac{(\tilde{Y}^i/P^i)}{R^i} = 1.$$

Composition Effect. An increase in the average energy intensity of production in a country (measured by the weighted average energy cost share) proportionately increases the country's carbon emissions:

$$\frac{\partial R^i}{\partial \bar{\alpha}_E^i} = \frac{\xi_R^i \tilde{Y}^i}{(1 + \lambda^i)r} > 0 \quad \text{and} \quad \frac{\partial R^i}{\partial \bar{\alpha}_E^i} \frac{\bar{\alpha}_E^i}{R^i} = 1.$$

Technique Effect. An increase in the fossil fuel resource price—either due to a higher world market price or due to a higher national carbon tax—proportionately *lowers* a country's carbon emissions:

$$\frac{\partial R^i}{\partial(r^i/P^i)} = -\frac{\xi_R^i \bar{\alpha}_E^i \tilde{Y}^i/P^i}{(r/P^i)^2} < 0 \quad \text{and} \quad \frac{\partial R^i}{\partial(r^i/P^i)} \frac{r^i/P^i}{R^i} = -1.$$

3 Data and Estimation

3.1 Data Sources

Our main data source is the Global Trade Analysis Project (GTAP) 10 database (Aguiar et al., 2019). From GTAP, we take the data on carbon emissions, sectoral production, trade flows, factor expenditures, and expenditure for and income from fossil fuels.⁷ GTAP also provides estimates for the sectoral elasticities of substitution of which we make use. Unfortunately, no estimate is available for the fossil fuel supply elasticity. For our main model, we therefore choose the simple average of the values reported by Boeters and Bollen (2012) for the three different specific fossil fuels oil, gas, and coal, namely $\eta = 2$.⁸

The GTAP 10 data is given for the base year 2014. We hence construct our whole data set for this year. It captures 140 countries (some of which are in fact aggregates of several countries) covering the whole world. We aggregate the sectoral structure to one non-tradable and 14 tradable sectors.⁹

For the gravity estimation of bilateral trade costs, we rely on a set of standard gravity variables from the CEPII dataset by Head, Mayer, and Ries (2010), namely bilateral distance (*DIST*), an indicator variable for whether two countries share a common border (*CONTIG*), and a second indicator variable for a common official language (*LANG*). We complement these variables by an indicator variable for joint regional trade agreement (*RTA*) membership taken from Mario Larch’s RTA database (Egger and Larch, 2008). We additionally construct a dummy variable that is equal to one for domestic trade flows and zero for all international trade (*INTRA*).

The (I)NDCs of the signatory states of the Paris Agreement are collected and made available online at the United Nations NDC Registry.¹⁰ To translate the different emission targets into 2030 BAU reduction targets, we additionally use GDP and carbon emission projections by the US Energy Information Administration’s (EIA) International Energy Outlook 2016.

The gravity and emission target data are aggregated to the regional structure of the GTAP data base.

⁷See Appendix C for details on the parametrization of the model.

⁸In our model extension presented in section 5 we can directly use Boeters and Bollen (2012)’s values, specifically $\eta_{oil} = \eta_{gas} = 1$, $\eta_{coal} = 4$.

⁹The 14 tradable sectors are agriculture, apparel, chemical, equipment, food, machinery, metal, mineral, mining, other, paper, service, textile, and wood. See Appendix A for the concordance to the 65 original GTAP sectors.

¹⁰See <https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx>. Note that countries continuously update their NDCs. Our calculations incorporate all updates up until April 2022.

3.2 Standardization of Reduction Targets

The reduction targets depicted in Figure 1 are percentage reductions of carbon emissions below the 2030 business as usual emission level.¹¹ They hence relate to the counterfactual emission level enforced in the counterfactual scenarios by $target^i = 1 - \overline{R^i}/R^i$. Note that while we calculate the reduction targets for the 2030 time frame, we will refrain from projecting all model variables and parameters to 2030 and therefore implement all scenarios as changes from the 2014 baseline equilibrium (implying that R^i refers to national emissions in 2014).

Different countries' (I)NDCs are specified in different ways, e.g. in terms of emission levels or intensities and compared to varying base years or to a BAU projection. In the simplest case, a country specifies a reduction target relative to BAU ($target = target_{BAU}^{NDC}$, suppressing the country superscript for ease of notation).

Some countries specify a specific targeted reduction of the *level* of emissions in 2030 compared to a reference (*ref*) year ($target_{level}^{NDC}$), as was e.g. the case for all targets in the Kyoto Protocol, which translates into our business as usual target as follows:

$$target = 1 - (1 - target_{level}^{NDC}) \frac{CO_{2,ref}}{CO_{2,2030}^{proj}}, \quad (17)$$

where $CO_{2,2030}^{proj}$ are projected BAU emissions in 2030.¹²

The final type of target is an emission intensity target. In this case, a country specifies the reduction of emissions per (value) unit of GDP it aims to achieve compared to a reference year intensity ($target_{int}^{NDC}$). This corresponds to a 2030 BAU target as follows:¹³

$$target = 1 - (1 - target_{int}^{NDC}) \frac{CO_{2,ref}/GDP_{ref}}{CO_{2,2030}^{proj}/GDP_{2030}^{proj}}. \quad (18)$$

Whenever countries reported a range for their targeted reduction, we chose the center of this range. We did not take into account additional, higher reduction promises that are conditional on other parties' behavior (e.g. financial support).¹⁴ Neither did we incorporate any other components of the NDCs beyond the greenhouse gas reduction commitments (such as additionally targeted renewable energy shares). In a few cases the combination of NDCs and GDP and emission projections imply a

¹¹Note that strictly speaking the targets refer to CO₂ equivalents of all greenhouse gas emissions. Due to better data availability, we use carbon emission paths for the projections to 2030.

¹²One country (Trinidad and Tobago) specifies its $target_{level}^{NDC}$ as a quantity of emissions rather than as a percentage. In this case, the expression becomes: $target = 1 - (CO_{2,ref} - target_{level}^{NDC})/CO_{2,2030}^{proj}$.

¹³Israel reported an intensity target per capita rather than per unit of GDP. In this case, simply substitute the *GDP* values by observed and projected population sizes.

¹⁴In some cases, countries did not specify which part of the target is conditional. We treated these commitments as entirely conditional.

target that represents an increase over the BAU emission path. For these Paris member countries, we assume in the counterfactual scenarios that they commit to not emit more CO₂ than in the BAU case (i.e. *target* = 0). For both level and intensity targets, some countries deviated from the 2030 target year and reported for instance targets for 2025. We treated these targets as if they were specified for 2030. Finally, some countries reported only certain mitigation actions rather than reduction targets or targets for specific sectors only. We treated these countries as committing to the BAU scenario (i.e. *target* = 0). Table 6 in Appendix C reports the targets that result from this procedure and which are used in our counterfactual analyses.

3.3 Selected Descriptive Statistics

Given the critical role of initial emission levels for the importance of the different national reduction targets (and, as will turn out, for the leakage potential), Figure 3 displays the national levels of carbon emissions. China and the US stand out as the strongest emitters, followed by other large developed or emerging economies, such as India, Russia, Japan, Germany, and Canada.

Figure 3: National Carbon Emissions in 2014

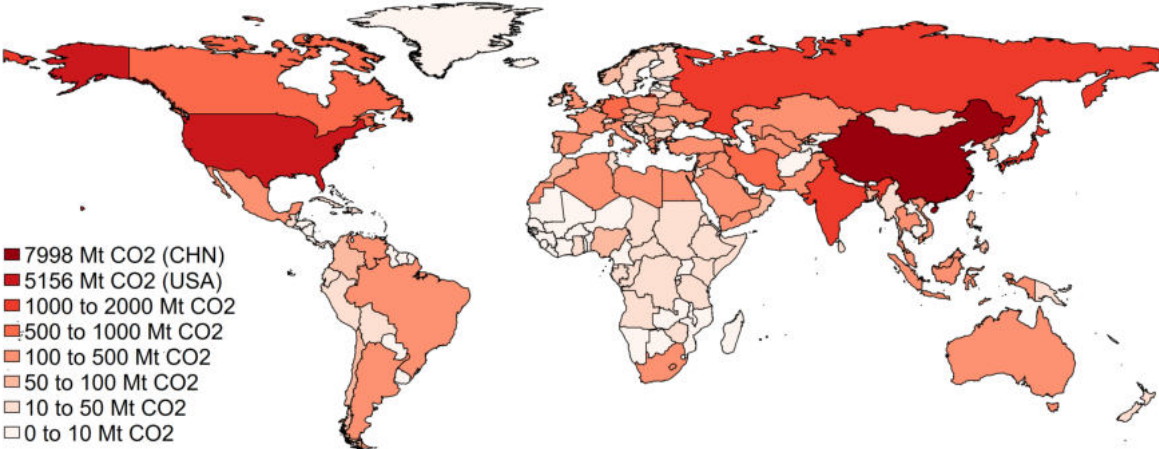


Table 2 additionally summarizes the gravity variables used in the trade cost estimation: country pairs are on average 7600 km apart, 2% share a common border, 11% share a common official language, and 27% are joint members of a regional trade agreement.

3.4 Gravity Estimation

Estimates of bilateral trade costs can be obtained based on the gravity Equation (12) derived above. Approximating trade costs by a function of observable bilateral characteristics (captured by the vector

Table 2: Gravity Variables

Variable	Obs	Mean	Std. Dev.	Min	Max
Distance (in km)	19,600	7554.06	4331.82	8.45	19781.39
Contiguity	19,600	0.02	0.14	0	1
Common Language	19,600	0.11	0.31	0	1
RTA	19,600	0.27	0.44	0	1

\mathbf{z}_{ij}), collecting all (partly unobservable) importer- and exporter-specific terms and introducing an error term yields the following regression equation:

$$X_l^{ij} = \exp(\pi_l^i + \chi_l^j + \mathbf{z}'_{ij}\beta_l) \times \varepsilon_l^{ij}. \quad (19)$$

Following the suggestions by Feenstra (2004) and Santos Silva and Tenreyro (2006), respectively, we capture π_l^i and χ_l^j by the inclusion of exporter and importer fixed effects and estimate the model in its multiplicative form (avoiding problems due to heteroskedasticity and zero trade flows) with the Poisson Pseudo Maximum Likelihood (PPML) estimator. The estimation results for all sectors are shown in Table 5 in Appendix B. Based on these coefficient estimates, we can construct an estimated trade cost matrix.

3.5 Model Validation

In this subsection, we briefly discuss how our model fits the data from the baseline equilibrium, as well as how its global emission reactions to a policy shock compare to other models in the literature.

As structural gravity models always do, our model perfectly replicates the national (sectoral) production values. Unsurprisingly, the workhorse model in international trade also fits the sectoral bilateral trade flows extremely well, indicated by an average Pseudo- R^2 from the gravity regressions of 0.97. Importantly, national carbon emissions are also perfectly fitted in our framework. The sectoral distribution of a country’s carbon emissions is closely proxied by the perfectly replicated distribution of sectoral energy expenditures.

To investigate whether the model predicts credible reactions to policy shocks (not only in terms of trade effects that are well established in the trade literature, but also in terms of emission changes), we simulate a counterfactual scenario in which all Annex I countries of the Kyoto Protocol reduce their emissions by 20% while all other countries undertake no climate policy and calculate the resulting leakage rate. This type of scenario has been investigated intensively in the literature and therefore can be compared nicely. Böhringer, Balistreri, and Rutherford (2012) implement the same scenario in a

number of CGE models using data for 2004 and find a range of leakage rates from 5 to 19%. Larch and Wanner (2017) obtain a leakage rate of 12.5% for the base year 2007. Elliott et al. (2010) consider the introduction of specific carbon tax rates rather than explicit reduction targets and—also using 2004 data—find leakage rates in the range of 15 to 25%, which increase in the level of the carbon tax. We simulate the 20% reduction scenario for the Annex I countries and find a leakage rate of 25.6%. The prediction of our model hence is at the high end of a typical range of results. However, in comparing the models’ predictions one should keep in mind that the Annex I countries covered a larger share of global emissions in 2004 than in 2014. Given the implied smaller coalition size in our case, leakage is expectedly somewhat higher in our simulation.

4 Counterfactual Analysis: Unilateral Withdrawals from the Paris Agreement

We use the model framework developed in Section 2 to investigate the effects of unilateral withdrawals from the Paris Agreement. We consider each of the 140 countries in our data set in turn, i.e. we run 140 different model simulations in all of which *all countries but one* fulfill the targets specified in their NDCs while one country does not undertake any policies towards its reduction aim and instead endogenously adjusts to the policies undertaken by the committed countries. We start this section off by discussing the results for two particularly important and illustrative examples, the US and China, before comparing results across the world.

4.1 The US Withdrawal

As discussed in the introduction, the mere erasure of the US target would cut the overall emission reduction of the Paris Agreement by 31.8%. But the calculation of this direct effect did not allow for an endogenous adjustment of the US to the climate policies of the Paris member countries, as the US were assumed to follow a BAU emission path rather than fulfill their NDC target. Simulating a US withdrawal as a counterfactual scenario in which all countries introduce carbon taxes that are sufficient to fulfill their reduction targets while the US introduces no carbon tax at all, we find that the US emissions *increase* by 9.5%. This implies a leakage rate of 9.4%, i.e. almost every tenth ton of CO₂ saved in the committed countries is offset by increased emissions in the US. Putting together the loss of the US target and the partial offset of the remaining countries’ targets via leakage, we find that a US withdrawal from the Paris Agreement lowers the achieved global emission reduction by

more than a third (38.2%). The vast magnitude of this number stresses the importance of the Biden Administration’s return to the Paris Agreement for global mitigation efforts.

As shown in Section 2.6, we can decompose the US emission increase into three components. It could stem from an overall increase in production (scale effect), a shift towards the production of more energy-intensive goods (composition effect), or the use of more fossil fuel intensive production techniques for a given scale and composition of the economy (technique effect). We find a zero scale effect, a very small composition effect (0.5%) and a very strong technique effect (8.2%).¹⁵ As explained above, the technique effect can occur either due to a carbon tax or due to changes in the world fossil fuel price. As the withdrawing country does not introduce a carbon tax, we can fully attribute the strong positive technique effect to a decline in the fossil fuel price in response to lower fossil fuel demand in the committed countries. US producers make use of this fall in the price to switch towards a more fossil fuel intensive production technique. These findings indicate that the leakage of carbon emissions into the US is almost entirely driven by the energy-market leakage channel. This insight relates to a strand of literature that stresses the role of the supply side in climate policies (cf. e.g. Sinn, 2008; Harstad, 2012; Jensen, Mohlin, Pittel, and Sterner, 2015; Kortum and Weisbach, 2021; Weisbach, Kortum, Wang, and Yao, 2022). If achieving the reduction targets in the rest of the world via carbon taxes (i.e. a demand-side climate policy) induces strong leakage towards the US, climate policies that try to directly limit the *supply* of fossil fuels might be offset to a smaller extent. In line with this type of reasoning, Asheim et al. (2019) make the case for a supply-side climate treaty, one of the arguments being exactly that it would make the Paris Agreement less vulnerable to free riders.

4.2 A Potential Chinese Withdrawal

China has ratified the Paris Agreement and—different than the US—has not expressed an intention to withdraw. The scenario of a Chinese withdrawal is therefore a much more hypothetical one. Given China’s role as the world’s largest emitter and its very different economic structure compared to highly developed countries (such as the US), we think it is nevertheless an illustrative example that is worth a closer look before moving on to comparing results across the world.

Given China’s mild reduction target, we showed in the introduction that the direct effect of removing the Chinese NDC had a far less detrimental effect on the global emission reduction (11.9%) than the US case. But again, this number was based on China following its BAU emission path. We find that Chinese emissions increase by 11.6% in response to the other countries’ carbon taxes if China does not

¹⁵Note that the decomposition relies on a total differential and therefore is a linear approximation around the baseline equilibrium. The three effects hence do not necessarily (and typically) exactly add up to the overall emission change.

introduce a climate policy of its own. Due to the very high level of Chinese emissions, this is equivalent to a 13.8% leakage rate, i.e. an even higher share of the rest of the world's emission reductions is offset than in the US withdrawal case. Putting the direct loss and the leakage effect together results in a total global emission reduction loss of 24.1% for a Chinese withdrawal from the Paris Agreement. Taking into account an endogenous reaction to the other countries' policies hence doubles the overall harm done to the effectiveness of the agreement in this case. As in the US case, the increase in Chinese emissions is almost entirely driven by the fall in the international price for fossil fuels (10.1%, compared to 0.1% scale and a 0.2% composition effect).

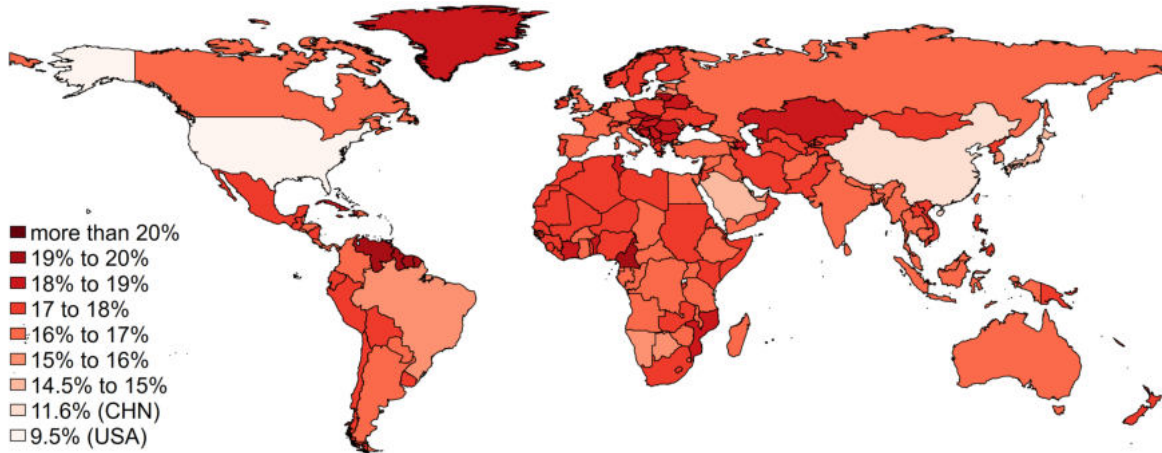
4.3 Results Across the World

We now turn to comparing the effects of unilateral withdrawals of all countries in our data set. Figure 4 shows the emission changes in every country if the rest of the world fulfills its targets and the respective country takes no climate policy action. Unsurprisingly, all countries endogenously react by increasing their emissions. As it turns out, the two examples considered so far (China and the US) are the countries with the smallest percentage emission increases. All other countries experience higher carbon emission increases in the range of 14.7 to 20.4%. Comparing the pattern to Figures 1 and 3, countries with a high overall level of emissions and/or very ambitious reduction targets appear to have lower increases of their emission levels. The reason is that countries with a high overall level of emissions and/or very ambitious reduction targets lead to larger reactions of world prices if they stick to their commitments and therefore reactions for other countries not sticking to their commitments will be larger.

To dig a little deeper into the differences in national emission effects, we can again make use of the decomposition. Two characteristics of our exemplary considerations hold up as global patterns: the almost complete absence of a scale effect (0.02% on average) and the predominant role of the technique effect (accounting for 92% of the emission increase on average). Different from the Chinese and US cases, the composition effects are non-negligible for many other countries (1.2% on average, ranging up to 3.9%). Figures 5 and 6 depict the technique and composition effects in the withdrawing countries, respectively.

Just as for the overall emission effect, the technique effect is smallest in the US and China. If one of these major emitters of carbon emissions is absent from the Paris Agreement, the fall in the demand for fossil fuels is strongly attenuated. This implies less pressure on the international fossil fuel price and hence a smaller incentive to shift towards more fossil fuel intensive production techniques. On the

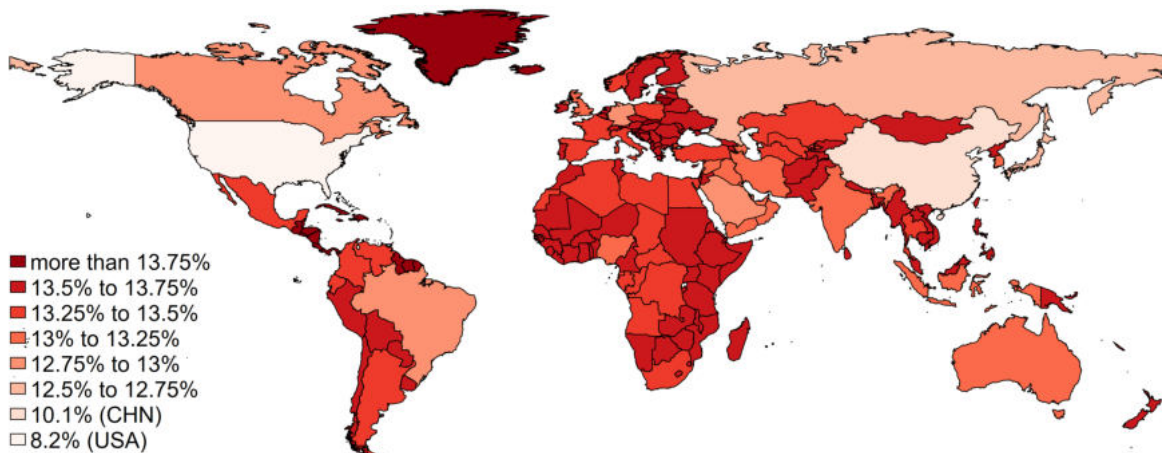
Figure 4: National Emission Effects



Notes: This figure shows the emission change in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. Emissions go up by 17.0% on average, ranging from 9.5% in the US to 20.4% in Trinidad and Tobago.

other hand, if a small country with a mild reduction target drops out of the agreement, almost the complete sum of national targets is still in place. Therefore, the fossil fuel price goes down by almost the full extent by which it would have been lowered in the case of full global compliance with the Paris Agreement and therefore the withdrawing country faces a very strong incentive towards “dirtier” production techniques induced by the lower fossil fuel price.

Figure 5: Technique Effects

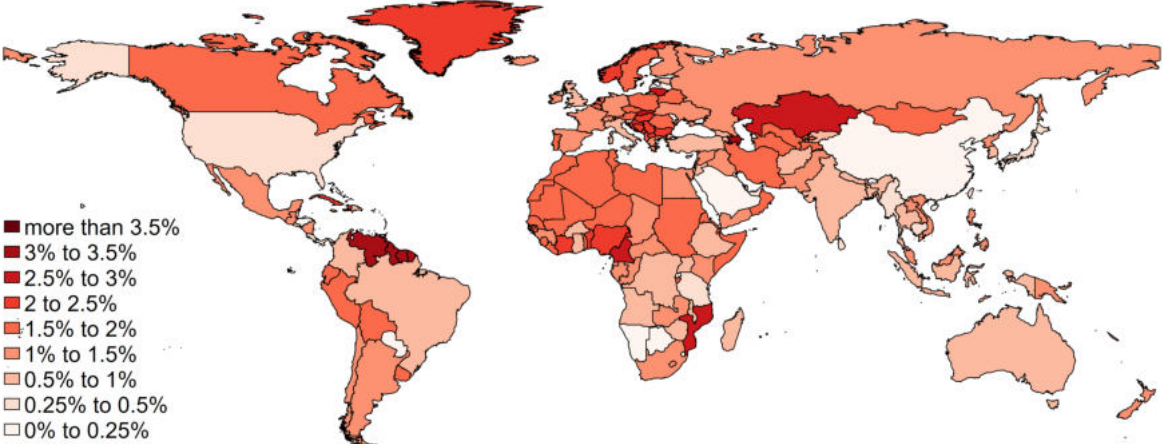


Notes: This figure shows the technique effect in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. The technique effect increases the withdrawing country’s emissions by 13.5% on average, ranging from 8.2% in the US to 13.8% for many countries.

More fossil fuel intensive production *techniques* for all goods are one reason why emissions in the withdrawing country can go up, another one is the possibility to specialize in the supply of goods from particularly emission-intensive *sectors*. This source of higher emissions is captured by the composi-

tion effect. While we found only small compositional changes in China and the US in case of their withdrawals, it is evident from Figure 6 that the same is not true for many other countries. Even though the composition effects are not as strong as the technique effects, most countries make use to a noticeable extent of the possibility to shift production towards emission-intensive sectors and then export these products to Paris Agreement member countries who partly pulled out of these sectors to achieve their emission reduction targets.

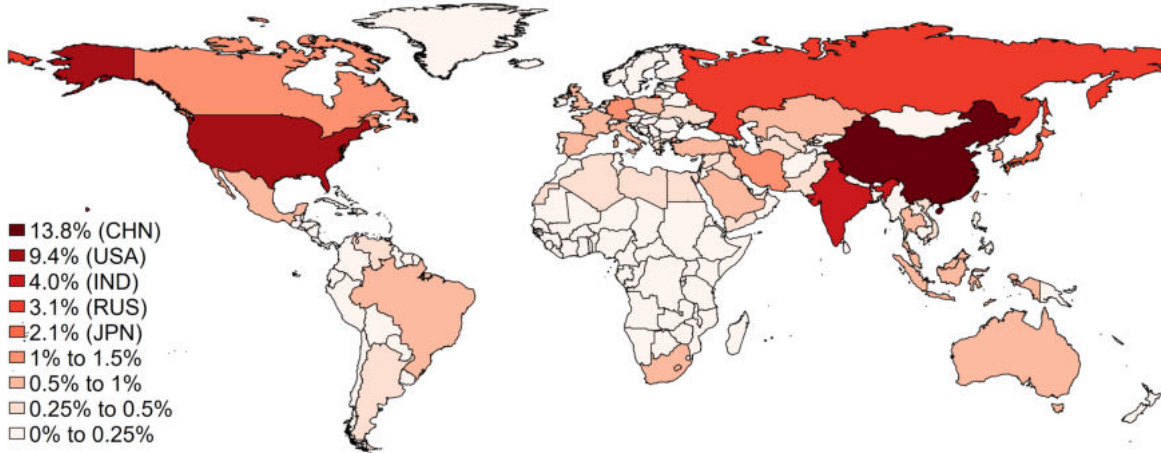
Figure 6: Composition Effects



Notes: This figure shows the composition effect in each country if the respective country withdraws from the Paris Agreement while the rest of the world fulfills its emission reduction targets. The composition effect increases the withdrawing country’s emissions by 1.2% on average, ranging from 0.0% in Namibia, Malta, Hong Kong, Botswana, and Luxembourg to 3.9% in Trinidad and Tobago.

After this closer look on how the national emission increases of withdrawing countries come about, let us focus on the implications of these endogenous adjustments for the global emissions. As illustrated above for the Chinese and US case, the emission increase in the withdrawing country partly offsets the global emission reduction from the remaining reduction targets, a phenomenon that is captured by the leakage rate. Figure 7 displays the different leakage rates that occur in the 140 withdrawal scenarios. Even though the US and China experience the lowest percentage emission increase, their very high levels of carbon emissions translates these comparatively small increases into the by far highest leakage rates. Already the withdrawals from the group of countries with the highest leakage rates after those two leading emitters (India, Russia, Japan, and Germany) offsets far lower shares of the world emission reduction (4.0, 3.1, 2.1, and 1.5%, respectively). As was illustrated by the consideration of the technique and composition effects above, leakage appears to be primarily driven by the energy market leakage channel, while leakage via the production shift and international trade channel plays a second-order role. For most countries, leakage is very small as their emissions make up only a small fraction of global emissions (the median leakage rate is 0.07%).

Figure 7: Leakage Rates

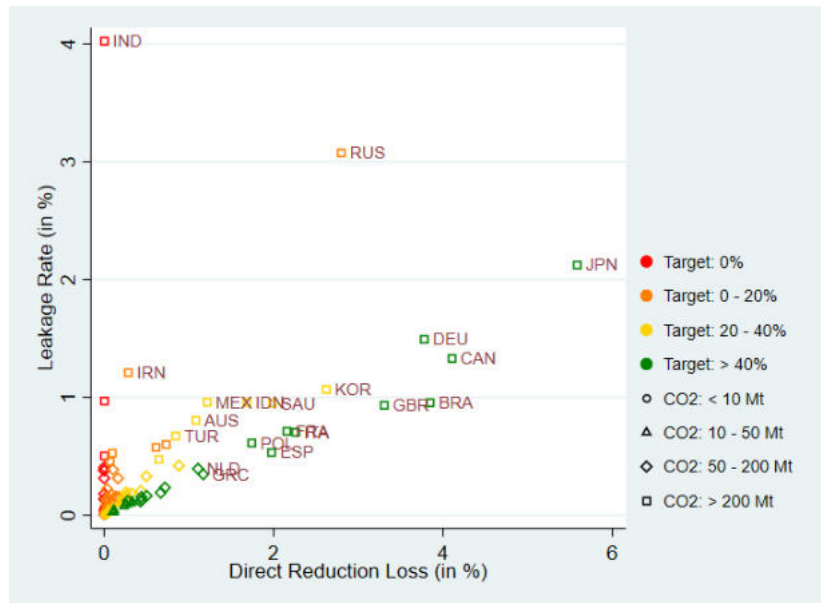


Notes: This figure shows the leakage rates that occur in the 140 different unilateral withdrawal scenarios from the Paris Agreement. On average, 0.4% of the rest of the world’s emission reduction is offset by emission increases in the withdrawing country. The leakage rates range between 0.0% for a number of very small countries and 13.8% for China.

Figure 8 summarizes the relationship between countries’ direct reduction losses and leakage highlighting the role of their national emission levels as well as their target reduction rates. It illustrates that while for leakage national emissions are the main driver, the direct reduction losses depend on both, national emission levels and the target. Starting from a vertical line of countries without a target, countries move in a clockwise direction when increasing their target reduction rate.

Putting together the direct emission reduction losses from removing a withdrawing country’s reduction target and the additional leakage losses due to endogenous adjustment towards higher emissions in the withdrawing country, we can obtain the total loss in the global emission reduction of the Paris Agreement induced by unilateral withdrawals. These total reduction losses are shown in Figure 9 and (for the five countries with the strongest effects) in Table 3. The announced US withdrawal has by far the worst impact on the Paris Agreement’s effectiveness to lower global emissions, followed by the also previously discussed Chinese case. All other unilateral withdrawals are significantly less harmful to the agreement’s capacity to lower world emissions. Nevertheless, a group of countries including e.g. several European countries (Germany, Italy, France, and the United Kingdom), other large developed countries (Japan, Canada, and South Korea), as well as three of the four remaining BRICS states (Brazil, Russia, and India) would still perceptibly lower the overall reduction (all in the range of 2.9 to 7.6%). One particularly noteworthy case is India (4.0%) for which the zero target (i.e. the target to not do worse than the BAU path) implied a zero direct effect. Taking into account its endogenous adjustment, it becomes evident that an Indian withdrawal would indeed harm the effectiveness of the Paris Agreement significantly. For all African countries, as well as for smaller and/or poorer Euro-

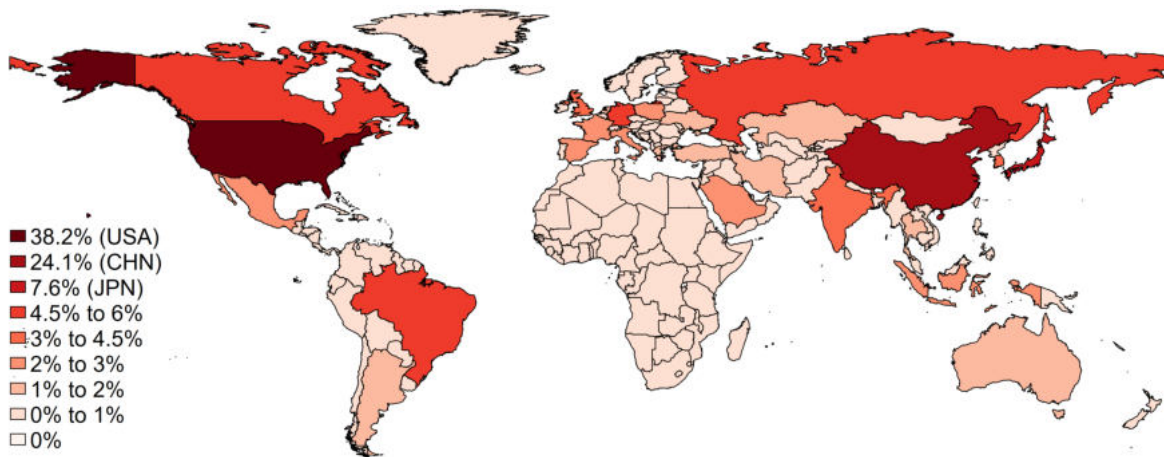
Figure 8: Direct Reduction Losses and Leakage



Notes: This figure shows the relationship between the leakage rate (in %) and the direct reduction losses (in %). Countries are depicted in different shapes and colors depending on their CO₂ emission levels and reduction targets, respectively. To be able to restrict the scale of the scatter plot, we leave out the US and China.

pean, Asian, or South American countries, even the total effect remains rather small, pulling down the average across all countries to a 1.1% reduction loss.

Figure 9: Total Emission Reductions Lost



Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to a unilateral withdrawal in the 140 different scenarios. On average, 1.1% of the global emission reduction are forgone. The loss shares range from 0.0% for a number of very small countries to 38.2% for the US.

Table 4 summarizes the results for all major variables of interest across the 140 different withdrawal scenarios that have been graphically shown above.

Table 3: Top Five Total Reduction Losses

Withdrawing country	USA	CHN	JPN	RUS	CAN
World reduction lost (total effect)	38.2%	24.1%	7.6%	5.8%	5.4%

Table 4: Unilateral Withdrawal Results

Variable	Obs	Mean	SD	Min	Max
Direct global reduction loss (in %)	140	0.71	2.96	0	31.80
Total global reduction loss (in %)	140	1.11	3.94	0.00	38.19
Leakage rate (in %)	140	0.43	1.48	0.00	13.84
Emission effect* (in %)	140	17.43	1.34	9.64	20.99
Scale effect* (in %)	140	0.02	0.08	-0.17	0.30
Composition effect* (in %)	140	1.22	0.78	-0.03	3.86
Technique effect* (in %)	140	13.49	0.60	8.17	13.84

Notes: For the variables marked by an asterisk, the national values of the withdrawing countries are shown.

4.4 A Potential EU Withdrawal

The European Union takes a special role in the Paris Agreement as all of its member countries are parties to the agreement individually, but at the same time the EU is a party of its own to the treaty. Therefore, even though an EU withdrawal would imply that a group of countries would drop out of the agreement, it can still be considered as a form of unilateral withdrawal and we hence briefly consider its effects here.¹⁶ The total reduction loss of the EU leaving the Paris Agreement is 23.1% and hence very similar to the effect of a Chinese withdrawal (24.1%). However, this large harm to the agreement’s effectiveness stems primarily from a very large direct reduction loss of 18.5% from removing the ambitious EU reduction pledges. The endogenous component, on the other hand, is way smaller in the European than in the Chinese case with a leakage rate of only 5.6%, i.e. less than half of what we found for a Chinese withdrawal. While these numbers stress the importance of the EU as a large player in multilateral climate policy, they also indicate that its importance stems primarily from its potential of leading the way in terms of particularly ambitious reduction targets.

4.5 Sensitivity: Varying the Fossil Fuel Supply Elasticity

One crucial model parameter for which we need to rely on values from the literature is the fossil fuel supply elasticity. In this subsection, we investigate the sensitivity of our results concerning the choice of η by considering the upper and lower bound of the range of elasticities used by Boeters and Bollen (2012) for their different fossil fuel types.

¹⁶Note that while all EU countries have the same reduction target of 55% below the 1990 emission level, this translates into different reductions compared to BAU. The standardized targets range from a mere commitment not to do worse than BAU in two Baltic countries (Estonia and Lithuania) to a very high 71% reduction target in Cyprus.

When increasing the fossil fuel supply elasticity from 2 to 5, the average global emission reduction loss decreases from 1.1% to 0.9%. The reduction loss induced by the US withdrawal still amounts to 34.6%. These somewhat lower effects are driven by lower leakage rates, which are roughly cut in half on average (0.2% instead of 0.4%). Intuitively, the reason for the lower leakage and overall smaller emission reduction losses is that fossil fuel suppliers react more strongly to falling prices by lowering the extracted quantities. This implies that the price in our new counterfactual equilibrium will decrease less, lowering the withdrawing country’s incentive to shift to a more emission-intensive production technique. Note that as a larger part of the reduction loss for China is due to leakage, a higher fossil fuel supply elasticity affects the Chinese withdrawal scenario specifically strongly: the reduction loss decreases from 24.1% to 17.2%.

When lowering the fossil fuel supply elasticity instead from 2 to 1, the average global emission reduction loss increases from 1.1% to 1.5%. In this case, a US withdrawal would eliminate 43.6% of the world emission reduction and a Chinese withdrawal would induce a 33.7% reduction loss. These larger effects are driven by relatively weaker quantity adjustments by fossil fuel suppliers in response to the falling fossil fuel price, inducing stronger leakage. Specifically, the average leakage rate roughly doubles compared to the benchmark $\eta = 2$ case to 0.85%, with the maximum in the case of a Chinese withdrawal as high as 24.7%. Further details on the results for the different values of η are presented in Appendix D.

5 Model Extension: Multiple Fossil Fuels

The model developed in Section 2 incorporated one single fossil fuel resource used in energy production and assumed emissions to be proportional to the fossil fuel usage. In this section, we allow for multiple fossil fuels with varying carbon intensities and potentially different supply elasticities.

5.1 Model

Fossil fuels used in country i are now treated as a composite of different types of fossil fuels (specifically oil, gas, and coal):

$$E^i = A_E^i \left(\prod_{v \in \mathcal{V}} (R_v^i)^{\rho_v^i} \right)^{\xi_R^i} \prod_{f \in \mathcal{F}} (V_{E_f}^i)^{\xi_f^i}, \quad (20)$$

with $\sum_{v \in \mathcal{V}} \rho_v^i = 1$. For each type of fossil fuel, supply is modeled with a separate CEFS function:

$$\widehat{R}_v^W = \left(\frac{\widehat{r}_v}{\widehat{P}_v} \right)^{\eta_v}, \quad (21)$$

with $\sum_{i \in \mathcal{N}} R_v^i = R_v^W$ and $\widehat{P}_v = \prod_{i \in \mathcal{N}} (P^i)^{\omega_v}$. Fossil fuel types differ in their carbon intensity (κ_v). Hence, emissions are no longer simply proportional to R_i , but rather given by:

$$EM^i = \sum_{v \in \mathcal{V}} \kappa_v R_v^i. \quad (22)$$

Countries implement carbon taxes that are equal per ton of CO₂ across fossil fuel types. Therefore, the percentage tax is no longer simply given by λ^i , but by $\kappa_v \lambda^i / r_v$. Additionally using the Cobb-Douglas structure, the national aggregate fossil fuel price is then given by:

$$r^i = \prod_{v \in \mathcal{V}} \left(\frac{(1 + \frac{\kappa_v \lambda^i}{r_v}) r_v}{\rho_v^i} \right)^{\rho_v^i}. \quad (23)$$

Market clearing for each fossil fuel type pins down their respective world market prices:

$$r_v = \frac{1}{R_v^W} \sum_{i \in \mathcal{N}} \left(\frac{1}{1 + \frac{\kappa_v \lambda^i}{r_v}} \right) \rho_v^i \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i \right). \quad (24)$$

To achieve its emission target, country i sets the carbon tax according to:

$$\overline{EM}^i = \sum_{v \in \mathcal{V}} \kappa_v \frac{\rho_v^i \xi_R^i (\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i)}{(1 + \frac{\kappa_v \lambda^i}{r_v}) r_v}. \quad (25)$$

In the absence of a target, there is no carbon tax levied (i.e. $\lambda^i = 0$). As there are multiple fossil fuels and countries can have different endowment shares for oil, gas, and coal (and the percentage tax rates vary across fossil fuel types), we also need to update the expression for a country's total income:

$$\begin{aligned} Y^i = & \sum_{f \in \mathcal{F}} \left[(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^i \right] \\ & + \sum_{v \in \mathcal{V}} \omega_v^i \sum_{j \in \mathcal{N}} \left(\frac{1}{1 + \frac{\kappa_v \lambda^j}{r_v}} \right) \rho_v^j \xi_R^j \left(\alpha_{SE}^j Y_S^j + \sum_{l \in \mathcal{L}} \alpha_{lE}^j Y_l^j \right) \\ & + \sum_{v \in \mathcal{V}} \left(\frac{\frac{\kappa_v \lambda^i}{r_v}}{1 + \frac{\kappa_v \lambda^i}{r_v}} \right) \rho_v^i \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i \right). \end{aligned} \quad (26)$$

Further, the aggregate fossil fuel price is now country-specific (due to compositional differences) and

already includes the tax, leading to the following new expression for the adjustment of the national energy price:

$$\widehat{e}^i = (\widehat{r}_i)^{\xi_R^i} \prod_{f \in \mathcal{F}} \left[\frac{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^{i'} + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^{i'}}{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^i} \right]^{\xi_f^i}. \quad (27)$$

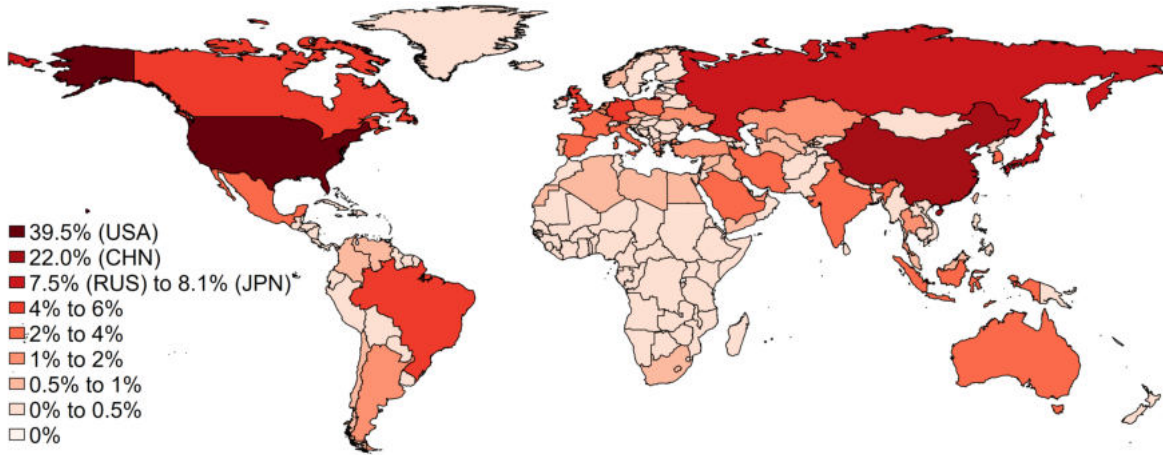
As in the base model, we again can decompose the emission changes into scale, technique, and composition effect. Additionally, there is a substitution effect resulting from the change in the fossil fuel mix. See Appendices E.1 and E.2 for details on the decomposition and parametrization of the extended model, respectively.

5.2 Results

Figure 10 summarizes the most important results of the simulation of unilateral withdrawals from the Paris Agreement in our extended model framework, namely the total percentage loss for the world emission reduction (i.e. it reproduces Figure 9 from the main model results). Reassuringly, the overall pattern bears striking resemblance to our previous results. The US withdrawal still has by far the strongest effect (39.5%), followed by China (22.0%) and then a group of countries with effects between about 5 to 8% including e.g. Japan, Russia, Canada, Germany, and Brazil. On average, the incurred loss is slightly higher when additionally allowing for substitution between different fossil fuel sources (1.2 vs. 1.1%). The largest differences occurs for Russia, whose withdrawal is associated with a 1.7 percentage points higher reduction loss, and China, whose withdrawal has a 2.2 percentage points *weaker* effect in the extended model.

To gain a better insight into the differences in outcomes for the base and extended model, Figure 11 displays the decomposition of the withdrawing countries' emission changes into scale, composition, technique, and substitution effect. As in the base model, the overall emission increases are primarily driven by the technique effects, i.e. generally more energy-intensive production. The new substitution effect in most cases additionally contributes to higher emissions in the non-committing countries. Hence, withdrawing countries shift within their fossil fuel mix from relatively cleaner gas and oil to the most emission-intensive coal. This is because the price decrease on the international coal market is particularly strong as coal is the most heavily taxed fossil fuel in the committed countries. However, there are a few notable exceptions, like China, India, Kazakhstan, and Poland, where the substitution effect counteracts the overall emission increase. This only occurs in countries with a high coal share in the initial fossil fuel mix. For example, if China does not participate in the Paris Agreement, there is

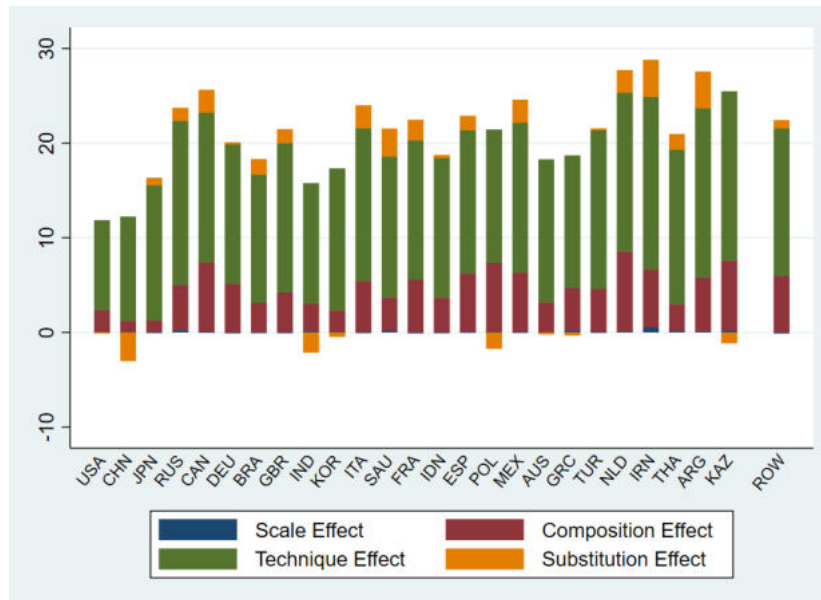
Figure 10: Total Emission Reductions Lost (Model Extension)



Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to a unilateral withdrawal in the 140 different scenarios (in the extended model). On average, 1.2% of the global emission reduction are forgone. The loss shares range from 0.0% for a number of very small countries to 39.5% for the US.

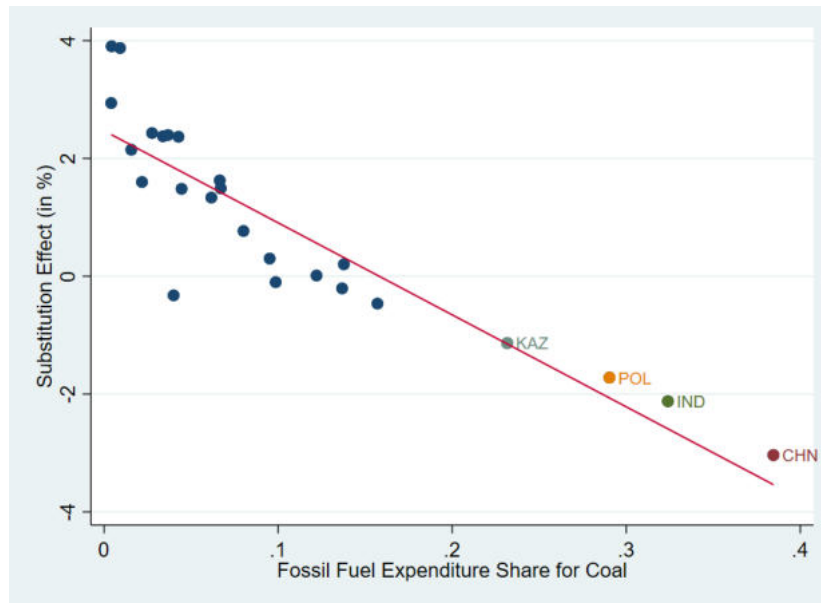
a smaller price decrease on fossil fuels compared to a scenario in which all countries fulfill their targets due to a smaller drop in the fossil fuel demand. As China has a coal-intensive energy mix, this drop is the smallest for coal. Hence, China substitutes coal with oil and gas, leading to a negative substitution effect. This relationship between the coal share and the substitution effect is illustrated in Figure 12.

Figure 11: Decomposition of Emission Changes (Model Extension)



Notes: This figure plots the decomposition of the emission changes into scale, composition, technique, and substitution effect for the 25 countries with the biggest reduction effect on world emissions and a rest of the world composite.

Figure 12: Scatter Plot of Substitution Effect against Coal Share



Notes: This figure plots the percentage substitution effect against the coal cost share in fossil fuel production for the 25 countries with the biggest reduction effect on world emissions.

6 Conclusions

Despite potential problems of enforceability and an overall lack of ambition in the NDCs, the Paris Agreement has an important strength: its global coverage. This strength, however, stands on shaky ground, as illustrated by not all signatory states moving forward to ratification of the agreement and by the (temporary) withdrawal of one of its major parties, namely the United States. In this paper, we analyze the consequences of unilateral withdrawals from the Paris Agreement on the achieved global emission reduction. To be able to account for both the direct effect of removing the withdrawing country's reduction target and the indirect effect of additional emission reductions due to carbon leakage, we develop an extended multi-sector structural gravity model featuring emissions from fossil fuel use, carbon taxes, and a constant elasticity fossil fuel supply function.

We find that single countries leaving the Paris Agreement can severely hurt the effectiveness of the treaty, the worst case being a US withdrawal which would eliminate more than one third of the overall emission reduction. Taking into account the endogenous emission adjustments beyond the mere absence of an emission target turns out to be of major importance, notably so in the Chinese case, in which the reduction loss doubles if carbon leakage is added to the direct effect. Using a decomposition of emission changes into scale, composition, and technique effects, we find that emission increases in withdrawing countries are mainly driven by a shift towards emission-intensive production techniques in response to a fall in the international fossil fuel price.

Both the overall magnitude of the reduction losses and the relative importance of the different leakage channels have significant policy implications. Most importantly, our findings imply that global coverage is indeed crucial for the overall mitigation success of the agreement and therefore strong political efforts should be made to keep all large emitters on board. Further, if the global coverage breaks down, our findings on the strong energy market leakage channel suggest considering new climate policy instruments that specifically tackle the fossil fuel supply.

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APPENDIX

A Sector Aggregation

The 15 sectors comprise the following GTAP 10 industries:

Agriculture: pdr (Paddy rice), wht (Wheat), gro (Cereal grains nec), v_f (Vegetables, fruit, nuts), osd (Oil seeds), c_b (Sugar cane, sugar beet), pfb (Plant-based fibers), ocr (Crops nec), ctl (Cattle, sheep, goats, horses), oap (Animal products nec), rmk (Raw milk), wol (Wool, silk-worm cocoons), frs (Forestry), fsh (Fishing).

Apparel: wap (Wearing apparel), lea (Leather products).

Chemical: chm (Chemical products), bph (Basi pharmaceutical products), rpp (Rubber and plastic products).

Equipment: eeq (Eletrical equipment), mvh (Motor vehicles and parts), otn (Transport equipment nec).

Food: cmt (Bovine meat products), omt (Meat products nec), vol (Vegetable oils and fats), mil (Dairy products), pcr (Processed rice), sgr (Sugar), ofd (Food products nec), b_t (Beverages and tobacco products).

Machinery: ele (Computer, electronic and optic), ome (Machinery and equipment nec).

Metal: i_s (Ferrous metals), nfm (Metals nec), fmp (Metal products).

Mineral: p_c (Petroleum, coal products), nmm (Mineral products nec).

Mining: coa (Coal), oil (Oil), gas (Gas), oxt (Other extraction).

Non-Tradables: ely (Electricity), gdt (Gas manufacture, distribution), wtr (Water), cns (Construction), osg (Public Administration and defense), edu (Education), hht (Human health and social work activities), dwe (Dwellings).

Other: omf (Manufactures nec).

Paper: ppp (Paper products, publishing).

Service: trd (Trade), afs (Accomodation, Food and service activties), otp (Transport nec), wtp (Sea transport), atp (Air transport), whs (Warehousing and support activities), cmn (Communication), ofi (Financial Services nec), ins (Insurance), rsa (Real estate activities), obs (Business services nec), ros (Recreation and other services).

Textile: tex (Textiles).

Wood: lum (Wood products).

B Estimation Results

Table 5: Gravity Estimation Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	agricult.	apparel	chemical	equipm.	food	machin.	metal
$\ln DIST$	-1.218 (0.132)***	-1.008 (0.120)***	-0.854 (0.112)***	-0.784 (0.097)***	-0.852 (0.074)***	-0.802 (0.154)***	-0.683 (0.099)***
$INTRA$	4.226 (0.394)***	2.588 (0.423)***	2.561 (0.245)***	2.418 (0.272)***	4.531 (0.206)***	1.831 (0.464)***	3.534 (0.219)***
$CONTIG$	0.320 (0.205)	0.534 (0.133)***	0.319 (0.146)**	0.571 (0.151)***	0.615 (0.143)***	0.010 (0.238)	0.520 (0.105)***
$LANG$	0.147 (0.149)	0.167 (0.153)	0.444 (0.123)***	0.122 (0.122)	0.467 (0.119)***	0.404 (0.213)*	0.432 (0.103)***
RTA	0.509 (0.190)***	0.231 (0.201)	0.365 (0.133)***	0.519 (0.170)***	0.751 (0.119)***	0.226 (0.183)	0.533 (0.100)***
N	19600	19600	19600	19600	19600	19600	19600
	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	mineral	mining	other	paper	service	textile	wood
$\ln DIST$	-0.893 (0.214)***	-1.119 (0.222)***	-0.573 (0.111)***	-0.976 (0.093)***	-0.154 (0.122)	-1.133 (0.083)***	-1.088 (0.115)***
$INTRA$	3.871 (0.496)***	3.595 (0.520)***	3.418 (0.431)***	3.668 (0.269)***	6.421 (0.367)***	2.788 (0.299)***	3.945 (0.285)***
$CONTIG$	0.469 (0.230)**	0.455 (0.370)	0.692 (0.186)***	0.622 (0.111)***	0.397 (0.190)**	0.116 (0.131)	0.866 (0.121)***
$LANG$	0.272 (0.199)	0.244 (0.206)	0.566 (0.137)***	0.386 (0.110)***	0.596 (0.117)***	0.165 (0.132)	0.120 (0.131)
RTA	0.369 (0.169)**	0.459 (0.192)**	0.080 (0.221)	0.514 (0.187)***	0.133 (0.137)	0.396 (0.172)**	0.358 (0.164)**
N	19600	19600	19600	19600	19600	19600	19600

Notes: All regressions include importer and exporter fixed effects. Standard errors clustered by exporter and importer are given in parentheses. * $p < 0.10$, ** $p < .05$, *** $p < .01$.

C Parametrization

In this section, we briefly describe how the model parameters can be obtained from the data. The Cobb-Douglas utility parameters γ_l^i and γ_s^i can be calculated as the sectoral expenditure shares. For the factor cost shares in the sectoral production functions, we first obtain the energy cost share by dividing firms' expenditure on intermediate inputs from the six GTAP energy sectors (coal, electricity, gas, gas manufacture and distribution, oil, and petroleum and coal products) by the firms' total costs. We then distribute the remaining cost share to the five GTAP factors (natural resources, capital, skilled labor, unskilled labor, and land) according to the reported relative expenses for these factors. The factor cost shares of the energy production function are determined similarly. First, we obtain the fossil fuel cost share. To ensure that we fit national emission levels, we multiply the world price

of fossil fuels per ton of carbon by the country's carbon emissions and divide it by the energy sectors' total costs. The remaining cost share is again distributed between the GTAP factors according to the factor expenditures. Finally, the national fossil fuel endowment shares are calculated by dividing a country's total revenue from the natural resource factor by the sum of these revenues in all countries.

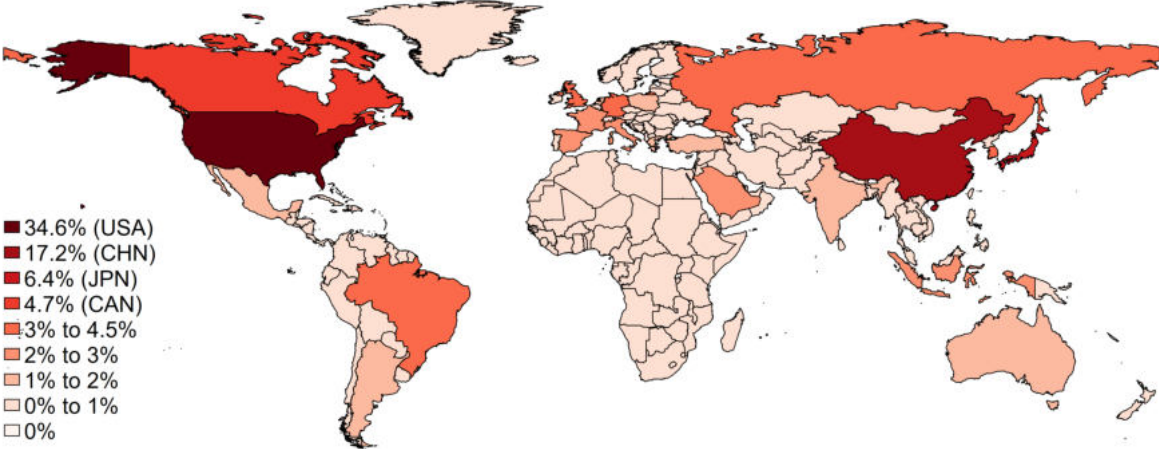
Table 6 shows the implemented reduction targets illustrated in Figure 1 and used in our counterfactual analyses.

Table 6: Implemented Reduction Targets (%)

ALB	20.90	ETH	14.00	MEX	22.00	THA	20.00
ARE	23.50	FIN	52.25	MLT	65.72	TJK	14.88
ARG	35.83	FRA	51.49	MNG	22.70	TTO	0
ARM	0	GBR	58.82	MOZ	0	TUN	0
AUS	22.05	GEO	0	MUS	14.00	TUR	21.00
AUT	61.48	GHA	1.54	MWI	6.00	TWN	0
AZE	16.62	GIN	9.70	MYS	2.96	TZA	0
BEL	54.88	GRC	58.05	NAM	14.00	UGA	6.60
BEN	12.50	GTM	11.20	NGA	20.00	UKR	23.49
BFA	19.60	HKG	55.31	NIC	0	URY	0
BGD	6.73	HND	0	NLD	49.98	USA	46.96
BGR	33.52	HRV	52.29	NOR	51.08	VEN	0
BHR	0	HUN	32.40	NPL	0	VNM	9.00
BLR	0	IDN	29.00	NZL	53.02	XAC	2.94
BOL	0	IND	0	OMN	4.00	XCA	0
BRA	64.92	IRL	54.15	PAK	0	XCB	1.89
BRN	20.00	IRN	4.00	PAN	0	XCF	12.31
BWA	33.10	ISR	27.00	PER	30.00	XEA	16.40
CAN	54.38	ITA	53.99	PHL	2.71	XEC	0.36
CHE	49.45	JAM	25.40	POL	50.10	XEE	6.66
CHL	30.00	JOR	5.00	PRI	62.73	XEF	0
CHN	11.35	JPN	41.11	PRT	64.96	XER	24.96
CIV	0	KAZ	19.82	PRY	10.00	XNA	30.65
CMR	12.00	KEN	6.72	QAT	25.00	XNF	4.78
COL	51.00	KGZ	15.97	ROU	15.14	XOC	9.76
CRI	41.20	KHM	0	RUS	15.08	XSA	0
CYP	71.15	KOR	40.00	RWA	16.00	XSC	7.50
CZE	38.37	KWT	7.40	SAU	31.33	XSE	3.08
DEU	42.39	LAO	60.00	SEN	7.03	XSM	0
DNK	41.09	LKA	4.00	SGP	0	XSU	0
DOM	7.00	LTU	22.87	SLV	0	XWF	3.17
ECU	9.00	LUX	54.65	SVK	31.88	XWS	2.44
EGY	0	LVA	0	SVN	58.62	ZAF	0
ESP	63.23	MAR	18.30	SWE	48.78	ZMB	0
EST	0	MDG	0	TGO	20.51	ZWE	0

D Sensitivity: Different Fossil Fuel Supply Elasticities

Figure 13: Total Emission Reductions Lost ($\eta = 5$)

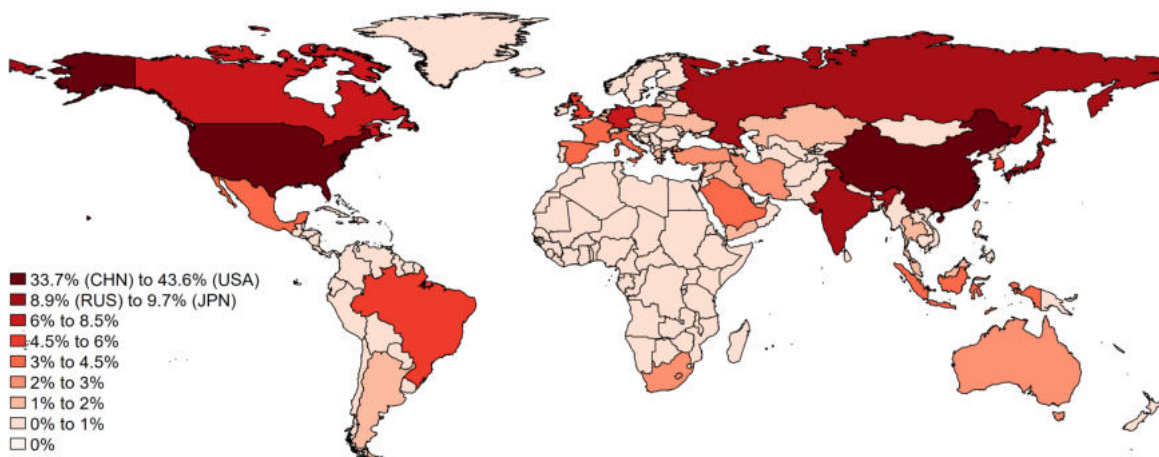


Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to a unilateral withdrawal in the 140 different scenarios with a fossil fuel supply elasticity of $\eta = 5$. On average, 0.9% of the global emission reduction are forgone. The loss shares range from 0.0% for a number of very small countries to 34.6% for the US.

Table 7: Top Five Total Reduction Losses ($\eta = 5$)

Withdrawing country	USA	CHN	JPN	CAN	DEU
World reduction lost (total effect)	34.6%	17.2%	6.4%	4.7%	4.4%

Figure 14: Total Emission Reductions Lost ($\eta = 1$)



Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to a unilateral withdrawal in the 140 different scenarios with a fossil fuel supply elasticity of $\eta = 1$. On average, 1.5% of the global emission reduction are forgone. The loss shares range from 0.0% for a number of very small countries to 43.6% for the US.

Table 8: Top Five Total Reduction Losses ($\eta = 1$)

Withdrawing country	USA	CHN	JPN	RUS	IND
World reduction lost (total effect)	43.6%	33.7%	9.7%	8.9%	8.1%

E Model Extension

E.1 Decomposition

Taking into account multiple fossil fuel types, country i 's emissions can be expressed as:

$$EM^i = \sum_{v \in \mathcal{V}} \kappa_v \frac{\rho_v^i \xi_R^i (\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i)}{(1 + \frac{\kappa_v \lambda^i}{r_v}) r_v} = \xi_R^i \bar{\alpha}_E^i \frac{\tilde{Y}^i}{P^i} \bar{\kappa}^i \left(\frac{r^i}{P^i} \right)^{-1},$$

where $\bar{\kappa}^i \equiv \sum_{v \in \mathcal{V}} \frac{\kappa_v \rho_v^i r^i}{(1 + \frac{\kappa_v \lambda^i}{r_v}) r_v}$ captures the average carbon intensity of a country's fossil fuel mix.

As in the base model, we can take the total differential and hence decompose the emission changes into different effects, namely scale, composition, and technique, as well as a new additional substitution effect, which captures shifts between different types of fossil fuel (e.g. substitution of coal with less emission-intensive fossil fuels to fulfill emission targets):

$$dEM^i \approx \underbrace{\frac{\partial EM^i}{\partial (\tilde{Y}^i/P^i)} d(\tilde{Y}^i/P^i)}_{\text{scale effect}} + \underbrace{\frac{\partial EM^i}{\partial \bar{\alpha}_E^i} d\bar{\alpha}_E^i}_{\text{composition effect}} + \underbrace{\frac{\partial EM^i}{\partial (r^i/P^i)} d(r^i/P^i)}_{\text{technique effect}} + \underbrace{\frac{\partial EM^i}{\partial \bar{\kappa}^i} d\bar{\kappa}^i}_{\text{substitution effect}}.$$

Scale Effect. A country's emissions increase proportionally with the size of the economy:

$$\frac{\partial EM^i}{\partial (\tilde{Y}^i/P^i)} = \frac{\xi_R^i \bar{\alpha}_E^i \bar{\kappa}^i}{r^i/P^i} > 0 \quad \text{and} \quad \frac{\partial EM^i}{\partial (\tilde{Y}^i/P^i)} \frac{(\tilde{Y}^i/P^i)}{EM^i} = 1.$$

Composition Effect. An increase in the average energy intensity of production in a country proportionately increases the country's carbon emissions:

$$\frac{\partial EM^i}{\partial \bar{\alpha}_E^i} = \frac{\xi_R^i \tilde{Y}^i \bar{\kappa}^i}{r^i} > 0 \quad \text{and} \quad \frac{\partial EM^i}{\partial \bar{\alpha}_E^i} \frac{\bar{\alpha}_E^i}{EM^i} = 1.$$

Technique Effect. An increase in the national fossil fuel resource price proportionately *lowers* a country's carbon emissions:

$$\frac{\partial EM^i}{\partial (r^i/P^i)} = -\frac{\xi_R^i \bar{\alpha}_E^i \bar{\kappa}^i \tilde{Y}^i/P^i}{(r^i/P^i)^2} < 0 \quad \text{and} \quad \frac{\partial EM^i}{\partial (r^i/P^i)} \frac{r^i/P^i}{EM^i} = -1.$$

Substitution Effect. An increase in the average carbon intensity of a country's fossil fuel mix proportionately increases the country's carbon emissions:

$$\frac{\partial EM^i}{\partial \bar{\kappa}^i} = \frac{\xi_R^i \bar{\alpha}_E^i \tilde{Y}^i}{r^i} > 0 \quad \text{and} \quad \frac{\partial EM^i}{\partial \bar{\kappa}^i} \frac{\bar{\kappa}^i}{EM^i} = 1.$$

The decomposition in the extended model hence captures the different emission channels very similar to the base model but allows further differentiation of the part of the change that takes place conditional on economic size and sectoral structure. While countries could simply produce more or less fossil fuel intensively (in response to a changing fossil fuel price) in the base model, they can still do so in the model extension, but can additionally shift between different fossil fuels based on relative price changes between them. We follow Pothen and Hübler (2018) in calling this latter channel the “substitution effect”.

E.2 Parametrization

We consider three different fossil fuel types, namely *oil*, *gas*, and *coal* (i.e. $\mathcal{V} = \{oil, gas, coal\}$). The GTAP fossil fuel sectors are: oil, gas, coa, p_c (Petroleum, coal products), and gdt (Gas manufacture, distribution). We collect gas and gdt in our *gas* resource and split p_c between our *coal* and *oil* resources according to the respective input expenditure shares for the GTAP oil and coa sectors.

For the carbon intensities of the different fossil fuels (κ_v), we rely on intensities given by the US EIA (<https://www.eia.gov/tools/faqs/faq.php?id=73&t=11>). For *coal*, we use the average over anthracite, bituminous, lignite, and subbituminous coal. For *oil*, we use the average over “diesel fuel and heating oil” and “gasoline (without ethanol)”. For *gas*, we use the value of “natural gas”.

Out of the five GTAP fossil fuel sectors, only coa, oil, and gas use the natural resource factor. Hence we can obtain fuel type-specific endowment shares as $\omega_v^i = NVFA_{NatRes,v}^i / \sum_j NVFA_{NatRes,v}^j$, where $NVFA_{NatRes,v}^i$ is expenditure on the GTAP natural resource factor (*NatRes*) for fossil type v in country i (using the GTAP labeling for the *NVFA* variable).

We calculate the fossil fuel production expenditure shares ξ_R^i and ρ_v^i in such a way as to exactly fit national carbon emissions from each fossil fuel type. We start by obtaining the emissions (EM_v^i) from the data. Then, resource quantities by fuel type can be obtained as $R_v^i = EM_v^i / \kappa_v$. We obtain the fossil fuel world market prices as $r_v = (\sum_i NVFA_{NatRes,v}^i) / (\sum_i EM_v^i)$. Then, the fossil fuel type cost shares in fossil fuel production and the fossil fuel cost share in energy production can be obtained as $\rho_v^i = (r_v R_v^i) / (\sum_u r_u R_u^i)$ and $\xi_R^i = (\sum_v r_v R_v^i) / (\alpha_{SE}^i Y_S^i + \sum_l \alpha_{lE}^i Y_l^i)$, respectively.