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The consequences of non-participation in the Paris Agreement☆

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ABSTRACT

International cooperation is at the core of multilateral climate policy. How is its effectiveness harmed by individual countries not participating in the global mitigation effort? We use a multi-sector structural trade model with carbon emissions from production and a constant elasticity of fossil fuel supply function to simulate the consequences of unilateral non-participation in the Paris Agreement. Taking into account both direct and leakage effects, we find that non-participation of the US would eliminate more than a third of the world emissions reduction (31.8% direct effect and 6.4% leakage effect), while a potential non-participation of China 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. In terms of welfare, the overwhelming majority of countries gain from the implementation of the Paris Agreement and most countries have only very little to gain from unilaterally deciding not to participate.

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)

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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.

While the reduction targets stated in the NDCs are very heterogeneous across countries, what is crucial and most likely explains at least part of the enthusiasm expressed in the first opening quote by former UN Secretary General Ban Ki-Moon is the fact that *every country* has a target. The sub-global coverage of the Paris Agreement's most prominent predecessor, the Kyoto Protocol, 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).

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.[1] Even though the United States has rejoined under Trump's successor Joe Biden, the episode 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 (we call this the "direct effects"). Second, and potentially just as importantly, non-participation can induce carbon leakage that lowers the achieved world reduction below the remaining sum of national targets.

Different from the direct effects, leakage effects (and hence the total effects) of unilateral non-participation 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 et al., 2012, for an overview of various prominent CGE models). A recent strand of literature (Egger and Nigai, 2015; Shapiro, 2016; Larch and Wanner, 2017; Larch et al., 2018; Shapiro and Walker, 2018; Farrokhi and Lashkaripour, 2021; Shapiro, 2021; Caron and Fally, 2022) incorporates environmental components into structural gravity models as an alternative approach.[2] Gravity models are the workhorse models in the empirical international trade literature. Just as CGE models, they can be used to conduct ex-ante analyses 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 non-participation in 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). This decomposition can generate important insights into the channels through which international climate policies are effective.

Our analysis of the effects of non-participation complements other studies that investigate the Paris Agreement and its implications. For example, Glanemann et al. (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 individual national goals are sufficient to jointly achieve the two (or even 1.5) degree Celsius target: they are not. Aldy and Pizer (2016), Aldy et al. (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, among 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 to 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 not participating in 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 presents our extended structural gravity model, shows how counterfactual analyses can be performed in this framework, and derives the emission change decomposition. In Section 3, the data sources

[1] Additionally, 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.

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

and descriptive statistics are presented, as well as the gravity estimation procedure. We discuss the results of simulating the non-participation for each country in Section 4. In Section 5, we derive a model extension with multiple fossil fuels of varying carbon intensities, leading to a fourth, substitution, effect on emissions, and rerun the simulations using the extended model. Section 6 concludes.

2. Model

In this section, we present an extended structural gravity model that includes multiple 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 with fossil fuel usage. The model builds on the framework by Larch and Wanner (2017), but deviates by (i) modeling the energy market leakage channel using a CEFS function,[3] (ii) linking emissions directly to fossil fuel use rather than to general energy use, and (iii) explicitly including a carbon tax that countries can use to achieve emission reduction targets.

2.1. Supply

2.1.1. Goods production

There is a set of countries $\mathcal{N}$ and a set of sectors $\mathcal{L}$. Each country $j \in \mathcal{N}$ produces a differentiated variety in each of the $l \in \mathcal{L}$ sectors according to the following Cobb–Douglas production function:

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

where A_l^i is a sector- and country-specific productivity parameter, α_{lE}^i, and α_{lf}^i denote production cost shares, 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_l^i denotes the energy input. Markets are assumed to be perfectly competitive and goods are hence sold at marginal costs:

$$p_l^i = \frac{\Gamma_l^i}{A_l^i} (e^i)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} (w_f^i)^{\alpha_{lf}^i}, \tag{1}$$

where $\Gamma_l^i = (\alpha_{lE}^i)^{-\alpha_{lE}^i} \prod_{f \in \mathcal{F}} (\alpha_{lf}^i)^{-\alpha_{lf}^i}$, e^i is the energy price in country i, and w_f^i are the factor prices.

2.1.2. Energy production

Different from the other production factors, countries are not endowed with a fixed energy supply, but the energy input has to be produced itself according to the following Cobb–Douglas production function:

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

where ξ_R^i and ξ_f^i denote the input cost shares and R^i is the usage of a fossil fuel resource. We abstract from trade costs in fossil fuels and assume that they are freely internationally tradable, implying a perfectly integrated world fossil fuel market.[4] A country's carbon emissions are modeled as proportional to its fossil fuel use.[5]

The energy price depends on the factor prices and technological parameters, as well as on the global fossil fuel price r. Additionally, countries can charge a carbon tax λ^i on the fossil fuel use:

$$e^i = \frac{\Gamma_E^i}{A_E^i} \left((1+\lambda^i) r\right)^{\xi_R^i} \prod_{f \in \mathcal{F}} (v_f^i)^{\xi_f^i}, \tag{2}$$

where $\Gamma_E^i = (\xi_R^i)^{-\xi_R^i} \prod_{f \in \mathcal{F}} (\xi_f^i)^{-\xi_f^i}$.

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[3] The 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.

[4] A very insightful paper that allows for a role of geography in one specific fossil fuel market (crude oil), is Farrokhi (2020). There, a gravity-type pattern arises due to a combination of fixed costs and unobserved refiner-supplier-pair frictions. Farrokhi (2020) finds the extent to which the oil market deviates from an integrated global market to be "modest", encouraging us in our simplifying assumption at this point, in particular as our counterfactual scenarios leave bilateral trade costs unaffected.

[5] Note that this implies two simplifications: the only type of greenhouse gas we account for in the model is CO_2 and in terms of CO_2, we account only for combustion emissions and abstract from process emissions (e.g. in cement production).

2.1.3. Fossil fuel supply

In modeling the global supply of the fossil resource R^W, we use a constant elasticity of fossil fuel supply function as proposed by Boeters and Bollen (2012):

$$R^W = \zeta\left(\frac{r}{P}\right)^{\eta}, \tag{3}$$

where ζ is a supply shifter, P a global price index, and η denotes the supply elasticity. The total fossil fuel supply R^W stems from the different countries according to their varying fossil fuel endowment shares ω^i (with $\sum_{i\in\mathcal{N}}\omega^i = 1$). These fossil endowment shares are also used to aggregate national price indices to the global level: $P \equiv \prod_{i\in\mathcal{N}}(P^i/\omega^i)^{\omega^i}$, with $P^i \equiv \prod_{l\in\mathcal{L}}(P^i_l/\gamma^i_l)^{\gamma^i_l}$, where γ^j_l represents country j's expenditure share for sector l.

As the name suggests, the chosen supply function ensures that the fossil fuel supply reacts with a constant elasticity to changes in the real fossil fuel price. As pointed out by Boeters and Bollen (2012), this is a difference (and advantage) in comparison to the more standard procedure of a nested production structure with a natural resource in fixed supply entering the uppermost nest.[6] Avoiding the assumption of a resource in fixed supply further allows us to link emissions directly to the quantity of the resource employed in production, rather than e.g. indirectly linking it proportionately to the energy use.

Note the key role of η for the energy market leakage channel. The more elastic the supply, the less a negative fossil fuel demand shock will change the fossil fuel price and hence the smaller the incentive for a country without its own climate policy to rely more heavily on fossil fuels and thus the smaller the energy market leakage effect.

2.1.4. Income

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

$$Y^i = \sum_{f\in\mathcal{F}} I^i_f + I^i_R + \left(\frac{\lambda^i}{1+\lambda^i}\right)\xi^i_R \sum_{l\in\mathcal{L}} \alpha^i_{lE} Y^i_l, \tag{4}$$

where $I^i_f \equiv w^i_f\left[V^i_{Ef} + \sum_{l\in\mathcal{L}} V^i_{lf}\right]$ denotes the factor incomes, $I^i_R \equiv \omega^i R^W r$ the fossil resource income, and $Y^i_l \equiv q^i_l p^i_l$ are the sectoral values of production.

2.2. Demand

2.2.1. Utility

Consumers in country j obtain utility according to the following utility function:

$$U^j = \left[\prod_{l\in\mathcal{L}}\left(\left[\sum_{i\in\mathcal{N}}(\beta^i_l)^{\frac{1-\sigma_l}{\sigma_l}}(q^{ij}_l)^{\frac{\sigma_l-1}{\sigma_l}}\right]^{\frac{\sigma_l}{\sigma_l-1}}\right)^{\gamma^j_l}\right]\left[\frac{1}{1+\left(\frac{1}{\mu^j}\sum_{i\in\mathcal{N}}R^i\right)^2}\right],$$

where β^i_l represents a preference parameter for goods from different origins, q^{ij}_l is the amount of good l from country i consumed in country j, σ_l stands for the sectoral elasticity of substitution, μ^j is a parameter that captures j's disutility from global carbon emissions, and R^i is country i's fossil fuel use which is proportional to its emissions. The utility function hence combines sectoral CES utility from consumption of goods from different origins 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 consumption decisions.

2.2.2. Gravity

Introducing iceberg trade costs T^{ij}_l (with $T^{ij}_l = T^{ji}_l \geq 1$ and $T^{ii}_l = 1$), we can express sectoral bilateral trade shares as an Eaton and Kortum (2002)-type gravity expression that contrasts country i's cost of serving market j (in terms of technology, input costs, and trade costs) to all other suppliers:

$$\pi^{ij}_l = \frac{\left(\beta^i_l p^i_l T^{ij}_l\right)^{1-\sigma_l}}{\sum_{k\in\mathcal{N}}\left(\beta^k_l p^k_l T^{kj}_l\right)^{1-\sigma_l}} = \left(\frac{\beta^i_l p^i_l T^{ij}_l}{P^j_l}\right)^{1-\sigma_l}. \tag{5}$$

Note that our calibration of the model will also include one non-tradable sector. This can simply be achieved in the model with infinite trade costs in the respective sector, implying fully domestic sourcing ($\pi^{ii}_l = 1$). The climate policies considered in this paper and discussed in more detail in the next section affect the production costs and hence the prices of producers in different countries and sectors differently and hence alter international trade patterns. This will capture the production relocation leakage channel, as low/no carbon price countries gain competitiveness and market shares in emission-intensive industries and hence specialize in these products.

[6] In this approach (taken e.g. in a paper on commodity trade by Fally and Sayre, 2018), the fossil fuel supply elasticity changes endogenously with the stringency of climate policy measures taken.

2.3. Climate policy

We will implement climate policy via carbon taxes in the model. Countries can charge a national carbon tax λ^i on the use of fossil fuels to fulfill specific emission targets $\overline{R}^i$. 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 not to participate in the agreement. We can use the scenario to pin down the chosen level 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[7]:

$$\lambda^i = \begin{cases} 0 \quad \text{if } i \notin cop, \\ \frac{\xi_R^i \sum_{l\in\mathcal{L}} \alpha_{lE}^i Y_l^{i\prime}}{\overline{R^{i\prime}} r'} - 1 \quad \text{if } i \in cop. \end{cases} \tag{6}$$

2.4. Trade balance, market clearing and equilibrium

Trade is assumed to be balanced and the national energy and factor markets, as well as the international goods and fossil fuel markets, are all assumed to clear:

$$\sum_{i\in\mathcal{N}} \sum_{l\in\mathcal{L}} \pi_l^{ij} \gamma_l^j Y^j = \sum_{j\in\mathcal{N}} \sum_{l\in\mathcal{L}} \pi_l^{ji} \gamma_l^i Y^i \tag{7}$$

$$E^i = \sum_l E_l^i \tag{8}$$

$$V_f^i = \sum_{l\in\mathcal{L}} V_{lf}^i + V_{Ef}^i, \tag{9}$$

$$Y_l^i = \sum_{j\in} \pi_l^{ij} \gamma_l^j Y^j, \tag{10}$$

$$R^W r = \sum_{i\in\mathcal{N}} \left(\frac{1}{1+\lambda^i}\right) \xi_R^i \sum_{l\in\mathcal{L}} \alpha_{lE}^i Y_l^i. \tag{11}$$

Definition 1. For given factor endowments V_f^i, productivities A_l^i and A_E^i, preference shifters β_l^i, and trade costs T_l^{ij}, an equilibrium under climate policy structure $\{cop, \overline{R}^i\}$ is a set of factor prices w_f^i, energy prices e^i, carbon taxes λ^i, a world fossil fuel price r, and global fossil fuel supply R^W that satisfy equilibrium conditions (1)–(11).

Note that the equilibrium could also be expressed for a given set of carbon taxes rather than for a given coalition with a set of emission targets. Then, λ^i becomes exogenous and we can drop Eq. (6) from the equilibrium conditions.

2.5. Equilibrium in changes

Following Dekle et al. (2007, 2008), we can re-express the equilibrium of our model in changes, as this allows us to perform counterfactual analyses without the need to identify the level of the factor endowments V_f^i, productivities A_l^i and A_E^i, and preference shifters β_l^i.[8] We follow their "hat notation" which indicates the change of the respective variables, i.e. $\hat{x} = \frac{x'}{x}$, where the prime indicates a counterfactual value in response to a policy shock and values without a prime correspond to the baseline equilibrium.

Definition 2. Let $\{v_f^i, e^i, r, R^W\}$ be a baseline equilibrium under climate policy structure $\{\lambda^i\}$ and $\{v_f^{i\prime}, e^{i\prime}, \lambda^{i\prime}, r', R^{W\prime}\}$ be a counterfactual equilibrium under climate policy structure $\{cop, \overline{R}^{i\prime}\}$. Then, $\{\hat{v}_f^i, \hat{e}^i, \widehat{1+\lambda^i}, \hat{r}, \widehat{R^W}\}$ satisfy the following equilibrium conditions (12)–(19):

Carbon tax change:

$$\widehat{1+\lambda^i} = \begin{cases} 1 \quad \text{if } i \notin cop, \\ \frac{\xi_R^i \sum_l \alpha_{E,l}^i \sum_j \hat{\pi}_l^{ij} \pi_l^{ij} \gamma_l^j Y^{j\prime}}{\xi_R^i \sum_l \alpha_{E,l}^i \sum_j \pi_l^{ij} \gamma_l^j Y^j} \left(\frac{\overline{R}^{i\prime}}{R^i} \hat{r}\right)^{-1} \text{if } i \in cop. \end{cases} \tag{12}$$

[7] Note that we treat the targeted emission level $\overline{R^{i\prime}}$ 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.

[8] In principle, it would also allow us to avoid identification of the iceberg trade costs. We nevertheless estimate these and use a fitted trade network for our baseline equilibrium. π_l^{ij} in the following hence refers to fitted rather than observed trade shares. Using fitted rather than observed trade shares avoids zero trade flows leading to the implicit assumption of infinite trade costs between some countries, as well as potential problems of overfitting (see Dingel and Tintelnot, 2021). Further, we can use the calculation of fitted trade shares to eliminate trade imbalances in the data that otherwise may lead to numeraire dependency or non-zero global imbalances in the counterfactual results (see Costinot and Rodríguez-Clare, 2014; Ossa, 2016).

Trade share change:

$$\hat{\pi}_l^{ij} = \frac{\left(\left(\hat{e}^i\right)^{\alpha_{E,l}^i} \prod_f \left(\hat{w}_i^f\right)^{\alpha_{f,l}^i}\right)^{1-\sigma_l}}{\sum_k \pi_l^{kj} \left(\left(\hat{e}^k\right)^{\alpha_{E,l}^k} \prod_f \left(\hat{w}_k^f\right)^{\alpha_{f,l}^k}\right)^{1-\sigma_l}}. \tag{13}$$

Price index change:

$$\hat{P}_l^j = \left(\sum_i \pi_l^{ij} \left(\left(\hat{e}^i\right)^{\alpha_{E,l}^i} \prod_f \left(\hat{w}_i^f\right)^{\alpha_{f,l}^i}\right)^{1-\sigma_l}\right)^{1/(1-\sigma_l)}. \tag{14}$$

Fossil fuel supply change:

$$\widehat{R^W} = \left(\frac{\hat{r}}{\prod_i \left(\prod_l \left(\hat{P}_l^i\right)^{\gamma_l^i}\right)^{\omega^i}}\right)^{\eta}. \tag{15}$$

Counterfactual income:

$$Y^{j\prime} = \sum_f \left(\hat{w}_f^j I_f^j\right) + \widehat{R^W}\hat{r} I_R^j + \left(\frac{\lambda^{j\prime}}{1+\lambda^{j\prime}}\right) \xi_R^j \sum_l \alpha_{E,l}^j \sum_i \hat{\pi}_l^{ji} \pi_l^{ji} \gamma_l^i Y^{i\prime}. \tag{16}$$

Factor price change:

$$\hat{w}_f^i = \frac{1}{I_f^i} \sum_l \left(\left(\alpha_{f,l}^i + \xi_f^i \alpha_{E,l}^i\right) \sum_j \hat{\pi}_l^{ij} \pi_l^{ij} \gamma_l^j Y^{j\prime}\right). \tag{17}$$

Energy price change:

$$\hat{e}^i = \left(\widehat{(1+\lambda^i)}\hat{r}\right)^{\xi_R^i} \prod_f \left(\hat{w}_f^i\right)^{\xi_f^i}. \tag{18}$$

Fossil fuel price change:

$$\hat{r} = \frac{\sum_i \left(\frac{1}{1+\lambda^{i\prime}}\right) \xi_R^i \sum_l \alpha_{E,l}^i \sum_j \hat{\pi}_l^{ij} \pi_l^{ij} \gamma_l^j Y^{j\prime}}{\sum_i \left(\frac{1}{1+\lambda^i}\right) \xi_R^i \sum_l \alpha_{E,l}^i \sum_j \pi_l^{ij} \gamma_l^j Y_j} \left(\widehat{R^W}\right)^{-1}. \tag{19}$$

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:

$$R^i = \frac{\xi_R^i \left(\sum_{l\in\mathcal{L}} \alpha_{lE}^i Y_l^i\right)}{(1+\lambda^i) r} = \xi_R^i \bar{\alpha}_E^i \frac{\tilde{Y}^i}{P^i} \left(\frac{r^i}{P^i}\right)^{-1}, \tag{20}$$

where $\tilde{Y}^i \equiv \sum_{l\in\mathcal{L}} Y_l^i$ denotes total (nominal) production, $\bar{\alpha}_E^i \equiv \sum_{l\in\mathcal{L}} \alpha_{lE}^i \frac{Y_l^i}{\tilde{Y}^i}$ 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[9]:

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

[9] Details on the three components are given in Appendix A

2.7. Welfare effects

Welfare changes are a combination of real income changes and changes in climate damages (i.e. in disutility from global emissions) and are given by:

$$\hat{W}^j = \frac{\hat{Y}^j}{\hat{P}^j}\left[\frac{1+\left(\frac{1}{\mu^j}R^W\right)^2}{1+\left(\frac{1}{\mu^j}R^{W\prime}\right)^2}\right].$$

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.[10] GTAP also provides estimates for the sectoral elasticities of substitution of which we make use.[11] 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 $\eta = 2$.[12]

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.[13]

For the gravity estimation of bilateral trade costs, we rely on a set of standard gravity variables from the CEPII dataset by Head et al. (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 with 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.[14] 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.

For climate damages, we calibrate the disutility parameter μ^j to the social cost of carbon estimate by Rennert et al. (2022). They estimate it to be 185 Dollars (in 2020 US dollars). Deflating their number to 2014 US dollars, we use a social cost of carbon of 168.53 Dollars. For the regional distribution of these damages, we rely on simulations by NGFS (2022), which in turn rely on the econometric climate damage estimates by Kalkuhl and Wenz (2020).[15,16]

The gravity, emission target, and climate damage data are all aggregated into the regional structure of the GTAP database.

3.2. National emissions and reduction targets

We illustrate the data for two key country characteristics: the level of its emissions and the reduction target specified in its NDC. Fig. 1 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.

To make NDCs comparable, we standardize all reduction targets to percentage reductions of carbon emissions below the 2030 business-as-usual emission level.[17] They hence relate to the counterfactual emission level enforced in the counterfactual scenarios by $target^i = 1 - \overline{R^{i\prime}}/R^i$.[18] Details on the standardization are given in Appendix D. Fig. 2 reports the targets that result from this procedure and which are used in our counterfactual analyses.[19]

[10] See Appendix B for details on the parametrization of the model.

[11] See Table B.1 for the specific values across sectors.

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

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

[14] See 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.

[15] Specifically, we use the national median GDP changes from NGFS (2022)'s model runs using the integrated assessment model REMIND with the 50th percentile temperature projections and the median damages from Kalkuhl and Wenz (2020) in a scenario in which all countries implement their NDCs.

[16] Finland, Mongolia, and the "Rest of European Free Trade Association" (comprising Iceland and Liechtenstein) are estimated to have positive effects of climate change according to these numbers. As our functional form does not allow for gains from climate change, we put their damages to zero. The "Rest of North America" (comprising Bermuda, Greenland, and Saint Pierre and Miquelon) is not covered by Kalkuhl and Wenz (2020) and we hence also put the corresponding damage to zero.

[17] Note that strictly speaking the targets refer to CO_2 equivalents of all greenhouse gas emissions. Due to better data availability, we use carbon emission paths for the projections for 2030.

[18] We calculate the reduction targets for the 2030 time frame, but 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).

[19] The exact values are given in Table D.1 in Appendix D..

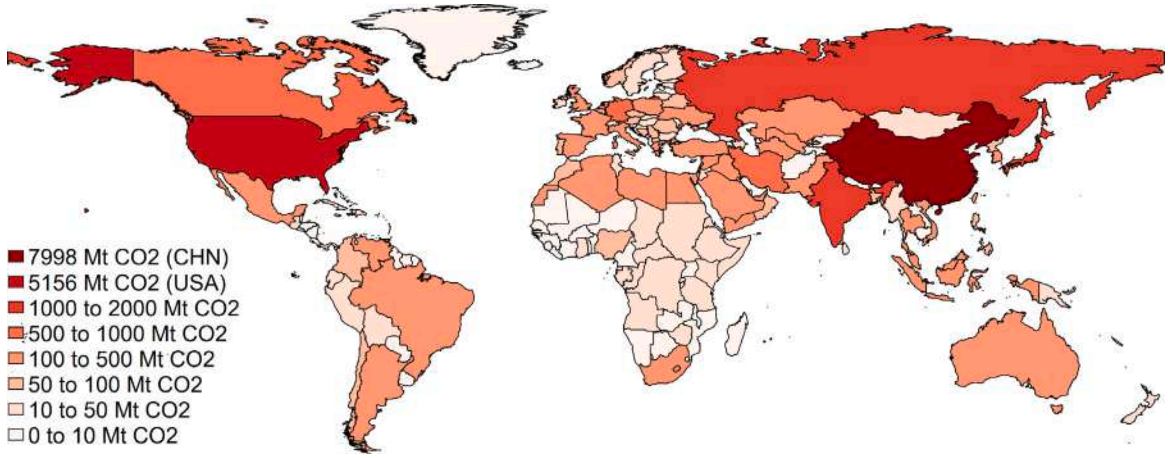

Fig. 1. National Carbon Emissions in 2014.

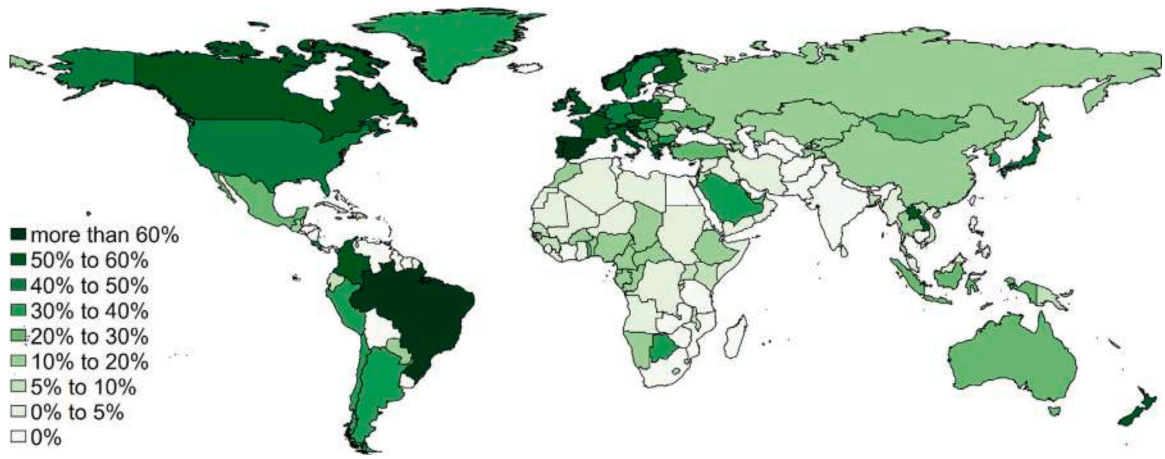

Fig. 2. Emission Reduction Targets in the Paris Agreement.
Notes: This figure shows the emission reduction targets specified in the individual countries' NDCs (or, where no NDCs are available, the Intended NDCs). To make the targets comparable, all are given as reductions below the business-as-usual emission path in 2030. National targets aggregate to a 25.4% global reduction compared to a BAU emission path.

The large heterogeneity in the 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 emissions by more than half. Aggregating all national targets implies a 25.4% reduction of global emissions compared to a BAU emission path.

3.3. Gravity estimation

Estimates of bilateral trade costs can be obtained based on the gravity Eq. (5) derived above. Approximating trade costs by a function of observable bilateral characteristics (captured by the vector $\mathbf{z}_{ij}$), collecting all (partly unobservable) importer- and exporter-specific terms and introducing an error term yields the following regression equation:

$$X_l^{ij} = \exp(\pi_l^i + \chi_l^j + \mathbf{z}'_{ij}\boldsymbol{\beta}_l) \times \varepsilon_l^{ij}, \tag{21}$$

where $X_l^{ij} = \pi_l^{ij}\alpha_l^j Y^j$ denotes trade flows from country i to country j in sector l. 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

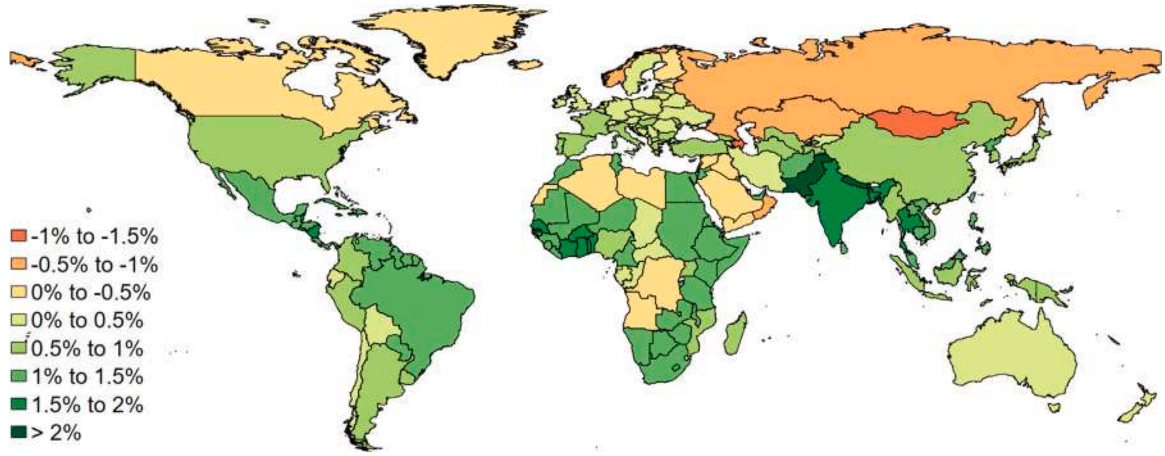

Fig. 3. Welfare Effects with Full Participation.
Notes: This figure shows the national welfare effects if all countries simultaneously put in place climate policies in line with their NDCs. 87% of all countries gain. On average, countries gain 0.78%, ranging from a 1.4% loss for Brunei to a 2.8% gain for Pakistan.

Pseudo Maximum Likelihood (PPML) estimator. The estimation results for all sectors are shown in Appendix E. Based on these coefficient estimates, we can calculate an estimated trade cost matrix from which we construct our fitted baseline trade shares.[20]

4. Results

To quantify the effects of non-participation, we proceed in two steps. First, we calculate the direct effect of not taking into account a non-participating country's emission reduction target. Based on national emission levels and the standardized targets of Section 3.2, these direct effects can be calculated directly without the need for a general equilibrium model. In order to additionally quantify endogenous adjustments, carbon leakage, and welfare effects, we then use the model framework developed in Section 2. 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 briefly discussing the case of global compliance with the agreement. We then move on to the consideration of non-participation of specific countries, where we will first consider two particularly important and illustrative examples, namely the US and China, before comparing results for countries across the world. We finish the section with a consideration of non-participation by the whole European Union.[21]

4.1. Global compliance

As already discussed in Section 3.2, if all countries fulfill their NDCs, global emissions are lowered by 25.4%. This can directly be calculated without the use of a model, solely based on emission and reduction target data. What our model can add even in the full compliance scenario, however, is a consideration of the welfare effects. Fig. 3 shows for all countries how their national welfare is affected in the full cooperation scenario in which all countries fulfill the pledges made in their NDCs. The overwhelming majority of countries (87%) gain from the global implementation of NDCs. While almost all countries face some real income losses due to the carbon pricing required to fulfill their NDCs,[22] these losses are mild in most countries and they are typically offset by lower climate damages. Countries experiencing a welfare loss from the global NDC implementation mostly have very high income from selling fossil fuels and in some cases low climate damages — consider e.g. Russia as an intuitive example. Countries gaining most from the agreement are the ones that are very vulnerable to climate change — consider e.g. the Indian subcontinent.

What could be done to increase the share of countries gaining from the agreement even further? While the geographical incidence of reduced climate damages cannot be altered, the same is not true for the incidence of what Kalkuhl and Brecha (2013) call the "climate rents", i.e. the scarcity rents for the limited remaining emissions. In line with most of the climate policy debate and initiatives, we implement the emission reductions via a tax on the *use* of fossil fuels, which allocates the rents to the countries demanding fossil fuels. Alternative climate policies, such as *extraction* taxes (discussed e.g. by Kortum and Weisbach, 2021, as part of an optimal unilateral climate policy mix), can shift rents towards countries supplying the fossil fuels. A suitable supply- and

[20] Appendix F gives an overview of the model fit in terms of trade and other key variables.
[21] A short sensitivity analysis for varying values of the elasticity of fossil fuel supply is presented in Appendix H..
[22] See Appendix G.1 for details on the real income effects.

demand-side policy mix may reduce welfare effect differences and make even more countries profit from the implementation of the Paris Agreement.

Besides the welfare effects, the simulation of the full compliance case also allows us to take a first look at the international fossil fuel market. As we have discussed, price effects on this market take center stage in one of the carbon leakage channels. We find that lower demand for fossil fuels resulting from the full implementation of all countries' NDCs puts considerable pressure on the real price of fossil fuels. Specifically, it drops by 13.6%. This already suggests that countries that decide not to take part in the mitigation efforts of the Paris Agreement will have strong incentives to make use of the low fossil fuel price and shift to more emission-intensive production techniques.

4.2. US non-participation

The United States is the world's second largest emitter of CO_2 and their NDC includes an ambitious reduction target of 47%. Combining these two aspects, we calculate that the mere erasure of the US target would cut the overall emission reduction of the Paris Agreement by almost a third (31.8%). The calculation of this direct effect assumes that the US follows a BAU emission path rather than fulfill its NDC target. It hence does not allow for an endogenous adjustment of the US to the climate policies of the Paris member countries. Using our general equilibrium model, we simulate US non-participation 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. In this case, 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 CO_2 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 US non-participation in 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 nearly zero scale effect, a very small composition effect (0.5%), and a very strong technique effect (8.2%).[23] As explained above, the technique effect can occur either due to a carbon tax or due to changes in the world's fossil fuel price. As the non-participating 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. Specifically, the real fossil fuel price on the world market falls by 8.2%.[24] 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 et al., 2015; Kortum and Weisbach, 2021; Weisbach et al., 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.

Our model also allows us to assess the welfare implications of the US non-participation. As expected, most countries (87%) are worse off if the US does not fulfill its NDC. On average, the national welfare changes of the full compliance case are lowered by 0.27 percentage points. The few countries gaining from the US non-participation are exactly the ones that would suffer welfare losses due to the agreement altogether. The additional US emissions do not hurt these countries strongly and at the same time, they experience real income gains because the US demands more fossil fuels. What about the US welfare effect? It turns out that the US itself does not profit from its non-participation. While its real income effect increases slightly in comparison to the full compliance scenario (0.1 p.p.), the additional climate damages due to the higher global emissions lower the US welfare gains from the agreement from 0.9 to 0.63%.

4.3. Chinese non-participation

China has ratified the Paris Agreement and – different than the US – has not expressed an intention to withdraw. The scenario of Chinese non-participation 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, the direct effect of removing the Chinese NDC is far less detrimental than in the US case. Specifically, the global emission reduction is lowered by 11.9%. But again, this number is based on China following its BAU emission path. Simulating the non-participation in our model, we find that Chinese emissions increase by 11.6% in response to the other

[23] Note 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.

[24] In comparison to the full compliance scenario, the real fossil fuel price (including the carbon tax) in the US is 50.9% lower if the US does not participate. This falls rather centrally into the range of real price changes for different fossil fuel types found by Nong and Siriwardana (2018) in their US withdrawal scenario (from 5.7% for petroleum products to 91.6% for coal).

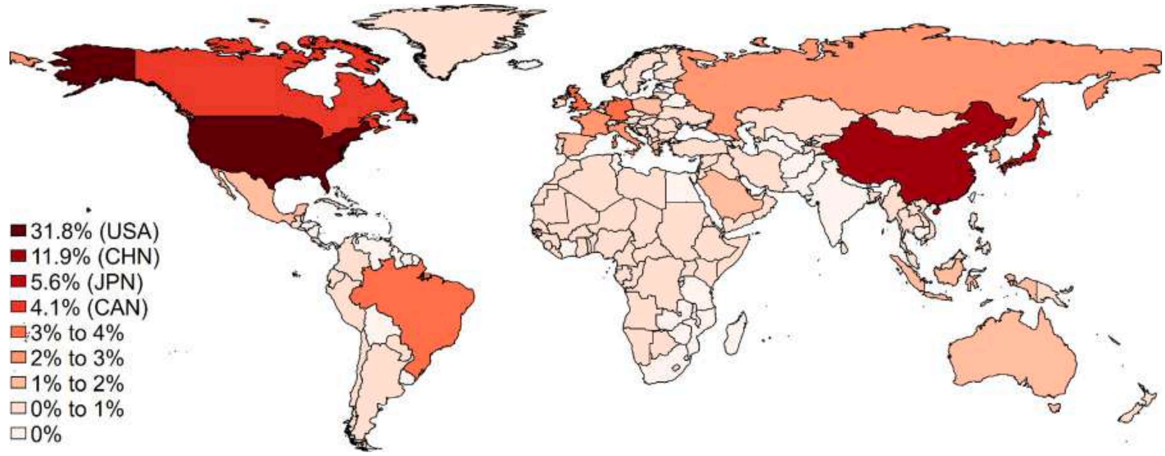

Fig. 4. World Reduction Lost by Withdrawn Commitments (Direct Effect Only).
Notes: This figure shows for every country in turn, which share of the world emission reduction due to the Paris Agreement is lost if the respective country does not participate in the agreement and its target specified in the NDC is hence no longer part of the global reduction. Endogenous adjustments of the non-participating country to other countries' climate policies with potentially resulting emission increases in the non-participating country beyond the BAU path are not taken into account at this point.

Table 1
Top five direct reduction losses.

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

countries' carbon taxes if China does not 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 non-participation case. Putting the direct loss and the leakage effect together results in a total global emission reduction loss of 24.1% for Chinese non-participation in the Paris Agreement. Taking into account an endogenous reaction to the other countries' policies 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). Also as in the US case, we find that China does not profit from its own non-participation. The emission increase drives up Chinese climate damages and reduces the Chinese welfare gain from the agreement by 0.21 percentage points.

4.4. Results across the world

We now turn to comparing the effects of unilateral non-participation of all countries in our data set.

4.4.1. Direct effects of lost reduction targets

Based on the national targets shown in Fig. 2 and data on the national emission levels in Fig. 1, we can calculate, without any further assumptions, the reduction of the aggregated national targets if some countries drop theirs. The corresponding numbers are shown in Fig. 4 and (for the five countries with the strongest effects) in Table 1.

Unsurprisingly, non-participation of the two world's leading emitters discussed in the previous subsections would directly lower the world emission reduction most strongly. Even though the US comes second in terms of emissions, its combination of large emissions with an ambitious NDC reduction target makes the direct effect of US non-participation the by far strongest of all countries (31.8% world reduction loss). China (11.9%) comes in second, while Japan (5.6%) has the third strongest effect. These two countries' strong effects come about in very different ways: very 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 non-participation 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 non-participating 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' non-participation is depicted with a zero effect

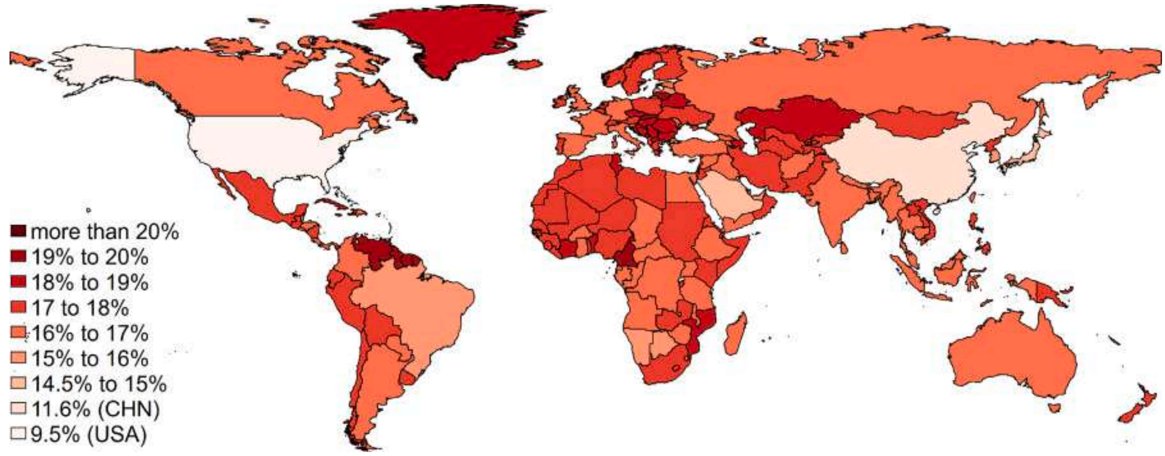

Fig. 5. National Emission Effects
Notes: This figure shows the emission change in each country if the respective country does not participate in the Paris Agreement while the rest of the world fulfills its emission reduction targets. Emissions go up by 17.0% on average, ranging from 9.5% in the US to 20.4% in Trinidad and Tobago.

in Fig. 4. But indeed, an Indian decision not to participate in the Paris Agreement and not to 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' non-participation.

4.4.2. National emission effects

Fig. 5 shows the general equilibrium, model-based 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 Figs. 1 and 2, 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. 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%).[25]

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 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 non-participating country faces a very strong incentive towards "dirtier" production techniques induced by the lower fossil fuel price.

More fossil fuel-intensive production *techniques* for all goods are one reason why emissions in the non-participating 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 composition effect. While we found only small compositional changes in China and the US in the case of their non-participation, 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.

4.4.3. Carbon leakage

After this closer look at how the national emission increases of non-participating countries come about, let us focus on the implications of these endogenous adjustments for global emissions. As illustrated above for the Chinese and US cases, the emission increase in the non-participating country partly offsets the global emission reduction from the remaining reduction targets, a

[25] Figures G.2 and G.3 in Appendix G depict the technique and composition effects in the non-participating countries, respectively.

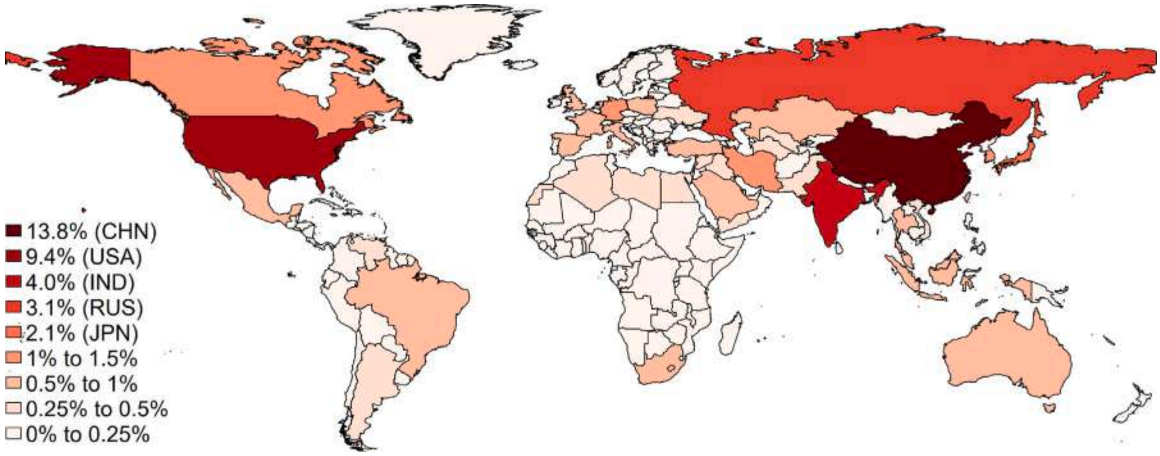

Fig. 6. Leakage Rates
Notes: This figure shows the leakage rates that occur in the 140 different unilateral non-participation scenarios from the Paris Agreement. On average, 0.4% of the rest of the world's emission reduction is offset by emission increases in the respective non-participating country. The leakage rates range between 0.0% for a number of very small countries and 13.8% for China.

Table 2
Top five total reduction losses.

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

phenomenon that is captured by the leakage rate. Fig. 6 displays the different leakage rates that occur in the 140 non-participation scenarios. Even though the US and China experience the lowest percentage emission increase, their very high levels of carbon emissions translate these comparatively small increases into the by far highest leakage rates (9.4 and 13.8%, respectively). Already the non-participation of 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). For many countries, leakage is very small as their emissions make up only a small fraction of global emissions (the median leakage rate is 0.07%).[26]

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. As already briefly discussed in the US case, this urges the participating countries to consider policies that not only limit their demand but also their supply of fossil fuels. This could also be targeted directly at the non-participating country in the form of a fossil fuel export tax (see e.g. Richter et al., 2018, for consideration of coal export taxes as a climate policy). Another, more prominent, policy instrument to tackle carbon leakage is a carbon border tax adjustment (see Böhringer et al., 2022, for a recent overview of the respective literature). Participating countries would charge a tariff on imports stemming from the non-participating country, the level of which would depend on the carbon content of the product. While such a mechanism may successfully reduce remaining leakage concerns via the competitiveness channel, it does not directly tackle the energy market leakage channel we find to be of particular importance.

4.4.4. Total emission effects

Putting together the direct emission reduction losses from removing a non-participating country's reduction target and the additional leakage losses due to endogenous adjustment towards higher emissions in the non-participating country, we can obtain the total loss in the global emission reduction of the Paris Agreement induced by unilateral non-participation. These total reduction losses are shown in Fig. 7 and (for the five countries with the strongest effects) in Table 2. The US non-participation has by far the worst impact on the Paris Agreement's effectiveness in lowering global emissions, followed by the also previously discussed Chinese case. Unilateral non-participation of any other country is 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 non-participation would indeed harm the effectiveness of the Paris Agreement significantly. These results stress the importance of global cooperation in climate change

[26] Figure G.4 in Appendix G illustrates the relationship between countries' direct reduction losses and leakage.

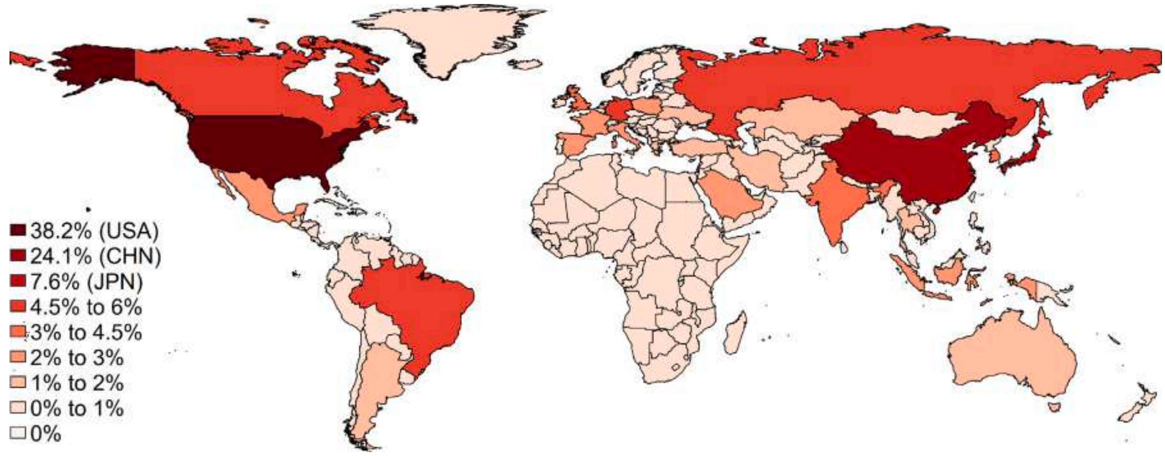

Fig. 7. Total Emission Reductions Lost
Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to unilateral non-participation in the 140 different scenarios. On average, 1.1% of the global emission reductions are forgone. The loss shares range from 0.0% for a number of very small countries to 38.2% for the US.

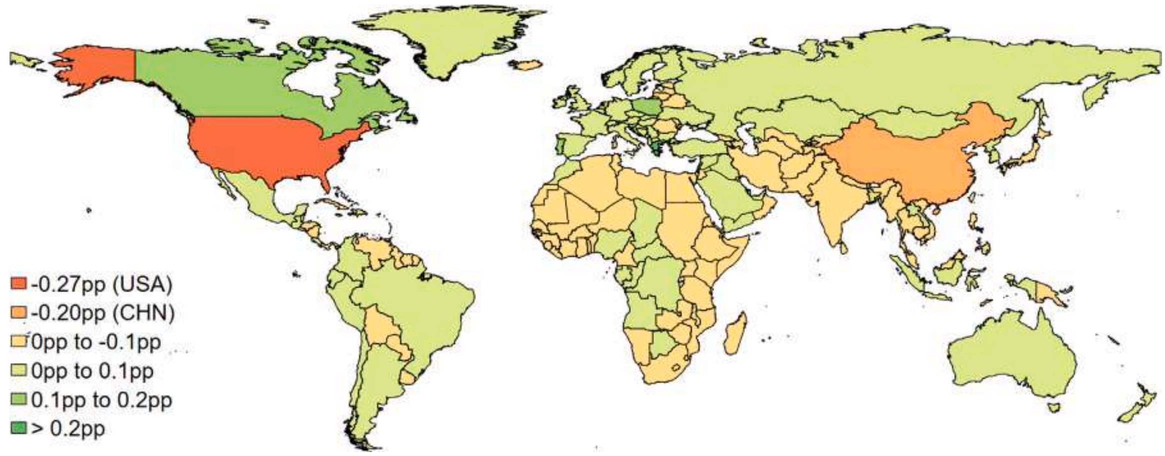

Fig. 8. Welfare Effects of Non-Participation
Notes: This figure shows the percentage point difference in national welfare effects in case of unilateral non-participation in comparison to the global compliance case. 53% of countries have a positive welfare effect. The average effect is 0.01 p.p. and the effects range from −0.27 p.p. for the US to 0.36 p.p. for Cyprus.

mitigation as they demonstrate that in many cases, non-participation of just a single country in the joint global effort severely damages the agreement's success.

For all African countries, as well as for smaller and/or poorer European, 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.

4.4.5. Welfare effects

We have shown in Sections 4.1 to 4.3 that the vast majority of countries gain from a global implementation of the NDCs and that both the US and China actually make themselves worse off by not participating in the agreement. We now consider the welfare effect of all countries in case of their unilateral non-participation. Fig. 8 shows the percentage point differences in the national welfare effects when not participating in comparison to global implementation.

It is evident that the US and China are the two countries that hurt themselves most by not participating. Their non-participation affects global emissions so strongly that they suffer a considerable increase in climate damages if they do not fulfill their NDCs. For most countries, the welfare effects of their unilateral non-participation are minor — 90% of the differences to the full compliance case fall in the range from −0.04 to 0.1 percentage points. 53% of countries gain, and the average effect is a mere 0.01 percentage point gain. Cyprus experiences the largest welfare gain from non-participation (0.36 p.p.). This is due to its reduction target (71%) being the most ambitious target of all countries, the implementation of which comes at a comparably high real income cost. Altogether, even aggregating the non-participation gains of all countries with a positive effect leads to gains that are a very small fraction (2.4%) of the global gains of implementing the Paris Agreement.

These welfare results seem to suggest that the free-riding problem in international climate cooperation (studied in detail by Nordhaus, 2015) may be solvable with relatively minor transfer payments. At the same time, examples such as the US under Donald Trump demonstrate that aggregate national welfare losses from non-participation do not necessarily keep countries in the agreement. This could be due to decision-makers taking into account only the (more immediate) real income effects of mitigation policies and ignoring the (more long-run) gains from reduced climate damages. Additionally, one can contemplate a role for other political economy factors (e.g. related to distributional considerations, regionally concentrated job losses, and lobbying) in determining countries' commitment to international climate change mitigation efforts (see e.g. Steckel and Jakob, 2021, for an overview of the political economy findings in the coal context).

4.5. EU non-participation

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 non-participation decision would imply that a group of countries would drop out of the agreement, it can still be considered as a form of unilateral non-participation and we hence briefly consider its effects here.[27] The total reduction loss of the EU leaving the Paris Agreement is 23.1% and hence very similar to the effect of Chinese non-participation (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 Chinese non-participation. 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 to lead the way in terms of particularly ambitious reduction targets.

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

We present the three model innovations in energy production, fossil fuel supply, and emission generation here and relegate details on the new model equilibrium to Appendix I.

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

$$E^i = A_E^i \left(\prod_{v \in \mathcal{V}} (R_v^i)^{\rho_v^i} \right)^{\xi_R^i} \prod_{f \in \mathcal{F}} (V_{Ef}^i)^{\xi_f^i}, \tag{22}$$

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

$$R_v^W = \zeta_v \left(\frac{r_v}{P_v} \right)^{\eta_v}, \tag{23}$$

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

$$EM^i = \sum_{v \in \mathcal{V}} \kappa_v R_v^i. \tag{24}$$

Emission taxes charged by Paris member countries to fulfill their reduction pledges take these carbon intensity differences into account and are e.g. hence higher in ad-valorem terms for coal than for gas, but equal across fuel types per ton of CO_2.

As in the base model, we can decompose the emission changes into scale, technique, and composition effects. Additionally, there is a substitution effect resulting from the change in the fossil fuel mix. See Appendices I.6 and I.8 for details on the decomposition and parametrization of the extended model, respectively.

[27] Note 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.

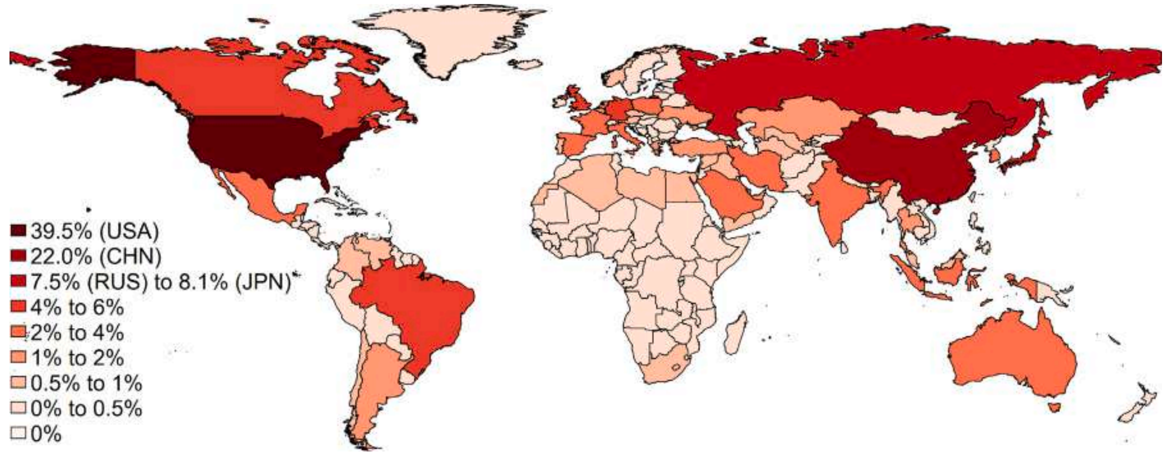

Fig. 9. Total Emission Reductions Lost (Model Extension)
Notes: This figure shows the shares of the global emission reduction due to the Paris Agreement that is lost due to unilateral non-participation in the 140 different scenarios (in the extended model). On average, 1.2% of the global emission reductions are forgone. The loss shares range from 0.0% for a number of very small countries to 39.5% for the US.

5.2. Results

Fig. 9 summarizes the most important results of the simulation of unilateral non-participation in the Paris Agreement in our extended model framework, namely the total percentage loss for the world emission reduction (i.e. it reproduces Fig. 7 from the main model results). Reassuringly, the overall pattern bears striking resemblance to our previous results. US non-participation 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 occur for Russia, whose non-participation is associated with a 1.7 percentage points higher reduction loss, and China, whose non-participation 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, Fig. 10 displays the decomposition of the non-participating 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, non-participating 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 will be a smaller price decrease on fossil fuels compared to a scenario in which all countries fulfill their targets due to a smaller drop in 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.[28]

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 non-participation in the Paris Agreement on the achieved global emission reduction. To be able to account for both the direct effect of removing the non-participating country's reduction target and the indirect effect of additional emission reductions due to carbon leakage, we use 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 not participating in the Paris Agreement can severely hurt the effectiveness of the treaty, the worst case being US non-participation 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 in the Chinese case, in which the reduction loss doubles if carbon leakage is added to the direct effect. Using a decomposition of

[28] This relationship between the coal share and the substitution effect is illustrated in Figure I.1 in Appendix I.

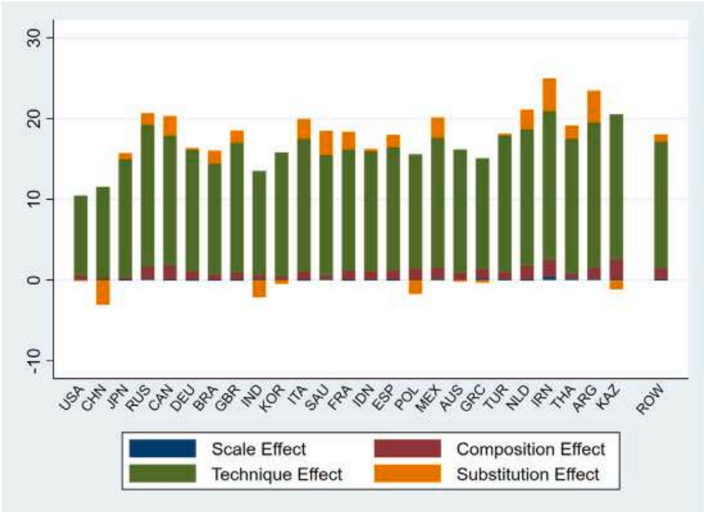

Fig. 10. Decomposition of Emission Changes (Model Extension)
Notes: This figure plots the decomposition of the emission changes into scale, composition, technique, and substitution effect for the 25 countries with the biggest reduction effect on world emissions and the rest of the world composite.

emission changes into scale, composition, and technique effects, we find that emission increases in non-participating 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.

Adding supply-side climate policies at the same time may have the potential to shift the incidence of climate rents and hence help avoid some countries losing from the implementation of the Paris Agreement, namely the major fossil fuel supply countries. Generally, however, the overall welfare effects of the agreement are overwhelmingly positive, and unilateral incentives for non-participation are weak. Further insights into the (political economy) drivers behind countries nevertheless questioning their mitigation efforts are needed in order to be able to design and evaluate policies that both effectively reduce carbon emissions and at the same time avoid feasibility pitfalls.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.euroecorev.2024.104699.

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