The Optimal Design of Climate Agreements

Inequality, Trade and Incentives for Climate Policy

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Thomas Bourany*

The University of Chicago

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Abstract

Fighting climate change requires ambitious global policies, which are undermined by free-riding incentives. Multilateral agreements and trade policies are usually proposed to address this issue, c.f. Nordhaus (2015). Moreover, climate policy has strong redistributive effects across countries due to inequality in income, climate impacts, effects on energy markets, and trade leakage, which exacerbate non-cooperation. In this context, how can we design a climate agreement that accounts for all these different channels to fight climate change? Through the lens of an Integrated Assessment Model (IAM) with heterogeneous countries and international trade, I study the "climate club" design to maximize world's welfare, choosing carbon and trade policies when countries can exit climate agreements. Participation constraints create a policy tradeoff between an intensive margin – a climate club with few countries implementing large emission reductions – and an extensive margin – accommodating a larger number of countries at the cost of lowering the carbon tax. I solve for the optimal climate club, which consists of all the countries at the exception of Russia, where the members impose a \$100 tax per ton of CO_2 and a 50% tariff on goods from non-members. Despite full discretion in the choice of carbon tax and tariffs, one cannot achieve the world's optimal policy, \$150 tax/ton CO_2, with complete participation. The tax is reduced to encourage participation but lowering it to include Russia would compromise climate action. I explore how additional instruments, such as transfers, as proposed in the COP's "loss-and-damage fund", or fossil-fuel specific tariffs, can increase abatement and welfare by mitigating the adverse redistributive effects of climate change and carbon taxation.

*Thomas Bourany, *thomasbourany@uchicago.edu*.

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1 Introduction

Fighting climate change requires ambitious global policies. Carbon emissions must reach net zero in the next decades, and our economies need to phase out fossil fuels in a concerted effort to keep temperature under $2°C$ and avoid catastrophic consequences of global warming c.f. IPCC et al. (2022). However, we are currently facing climate inaction, and the main reason behind this lack of cooperation is the presence of free-riding in climate policy. The benefits of fighting climate change are global while the costs of reducing emissions, in particular with carbon taxation, are local. Individual countries have incentives to free-ride on the rest of the world's reduction in emissions without implementing costly carbon abatement themselves.

Moreover, taxation of carbon and fossil fuels have strong redistributive effects, changing the willingness of countries to implement climate policy. First, emerging economies may face challenges in reducing fossil fuel consumption necessary to continue their economic development. Second, carbon taxation has substantial impacts on energy markets, between of fossil fuels exporters and importers. Finally, imposing a carbon tax in one country reallocates economic activity, and carbon emissions, toward other countries through international trade – known as the "carbon leakage". All these effects reinforce free-riding incentives and climate inactions.

Multilateral climate agreements have been the traditional answer to address climate inaction, as the United Nations Conference of the Parties (COP) for example. More recently, trade instruments have been the focus of policy discussions as trade policy offers the potential to give incentives to other countries to reduce emissions. In particular, Nordhaus (2015) proposes the idea of "climate club", which are voluntary agreements where members implement carbon taxation as well as retaliatory tariffs on countries that do not participate in the club. In this context, trade sanctions are necessary to foster participation to a club and reduce free-riding incentives.[1]

In this context, what should be the design of a climate agreement that accounts for free-riding incentives as well as redistributive effects? What is the optimal climate club? This paper addresses this question by examining the conditions necessary to construct a universal climate agreement with globally optimal carbon tax and tariffs. I explore which factors incentivize countries to join such an agreement, and I investigate how carbon and trade policy needs to be implemented to promote participation, maximize welfare and fight climate change.

In this project, I tackle these policy questions in a Climate-Economy framework augmented with heterogeneous countries and international trade. I build a multi-country Integrated Assessment Model (IAM), extended with trade in goods à la Armington and energy markets in fossil fuels. Individual countries differ in their vulnerability to climate change, income levels, energy mix as well as their positions as exporters or importers of goods and energy. In this framework, I account

[1] Another notable example is the European Union's Carbon Border Adjustment Mechanism (CBAM) which is proposed to address the climate leakage. This policy is a "carbon tariff" – i.e. a tariff whose rate increases with the carbon content of the good imported. This also has the potential to generate incentives for trade partners to implement climate policy in order to lower the carbon footprint of their exports.

for the multifaceted redistribution and leakage effects that arise in general equilibrium as a result of climate policy. This serves as a laboratory for evaluating the welfare effects of different agreement designs.

With endogenous participation, countries have differing incentives to join a climate agreement. As a result, the decisions on the optimal levels of carbon tax and trade tariffs, as well as the choice of participants in the club should be made jointly. Indeed, the optimal design reveals a tradeoff between an intensive and an extensive margin. At the intensive margin, an agreement could gather a small set of countries, which can individually implement large emissions reductions with high carbon taxes. However, this may be hardly satisfying to reduce global emissions and combat climate change effectively. In contrast, building a more extensive climate club requires to accommodate the participation of a larger number of countries, which can only be done at the cost of lowering the carbon tax.

In this context, I address the policy problem where a global social planner maximizes the world's welfare by designing a climate agreement that consists of three elements: (1) the set of countries that are included in the agreement – also called "climate club" or "climate coalition" – and that are subject to the climate and trade policies, (2) the level of the carbon tax that club members set on their oil, gas and coal energy consumption and (3) the level of the trade tariffs that the members impose on the goods imported from non-member countries – either uniform tariffs as in Nordhaus (2015) or carbon-border adjustment mechanisms (CBAM) as proposed in the European Union.

Countries make an individual choice to join or leave the agreement, and such strategic participation needs to be accounted for in the design of the agreement. I consider Nash equilibria where countries take participation decisions either unilaterally, or with "coalition deviations", i.e. when a subset of countries decide jointly to deviate and leave the agreement. The policy thus mirrors an optimal taxation and trade policy problem with limited instruments, assorted with a choice of countries. Given policy instruments, the coalition choice resembles a combinatorial discrete choice problem (CDCP) that can arise in trade economics. I propose different numerical solution methods to tackle this problem in presence of participation constraints.

I contrast this framework with global policy benchmarks absent endogenous participation. First, I consider the optimal carbon policy when the coalition gathers the entire world, without participation constraints. I show that the choice of the carbon tax depends crucially on the availability of redistribution instruments in the First-Best allocation. Without such instruments, such as lump-sum transfers, I show how the choice of the carbon tax accounts for distributional motives. Indeed, the carbon tax accounts for income inequality and its effect on trade leakage, as well as demand distortions and supply redistributions through fossil fuels energy markets. As a result, the optimal carbon tax is \$150 per ton of CO_2, and is lower than the Social Cost of Carbon, i.e. the marginal cost of climate change, a result that contrast with the standard Pigouvian recommendation.[2]. Second, I also compare the "climate club" framework to the non-cooperative Nash equilibrium, in which each individual countries choose their "unilaterally optimal" carbon taxation and trade tariffs. The unilateral carbon tax policy becomes a subsidy to increase production and revenues and tariffs are used for terms-of-trade manipulation.

In comparison, climate agreements provide an "issue linkage", c.f. Maggi (2016) by coupling the implementation of climate policy with a reduction in tariffs, as there would be free trade among coalition members. We see that the countries' participation choice depends on the balance between two effects: the distortionary cost of carbon tax against the cost of tariffs, which is related to gains from trade. To choose whether to exit the agreement, individual countries consider if the first outweighs the second. This is the case for fossil-fuel producers or several developing economies. Consequently, they would not participate in a climate agreement unless the carbon tax is decreased.

As a result, the optimal climate club consists of all countries at the exception of Russia and the agreement imposes a moderate carbon tax of \$100 per ton of CO_2, and a 50% tariff on traded goods of non-participants. The optimal climate agreement cannot achieve the world's optimal policy with complete participation – an agreement with a \$150 carbon tax and all the countries – despite full discretion on the choice of the carbon tax and tariffs.

First, to increase participation, it is beneficial to reduce the carbon tax. Several Middle Eastern countries, and several developing economies in South-Asia and Africa would not join an agreement with high carbon tax, and this for any tariffs. It is therefore optimal to lower the tax by 35% to include those countries, and share the "burden" of carbon abatement across more countries.

Second, it is beneficial to leave several fossil fuels producing like Russia and former soviet countries outside of the climate agreement. Indeed, they suffer large welfare costs from carbon taxation, being relatively cold, closed and exporters of oil and gas. They would never join an agreement, unless the carbon tax would be very small, which is not optimal from a global perspective.

Third, trade policy is a key strategic instrument to undermine free-riding and incentivize countries to join the agreement. All the countries for which the cost of large tariffs outweighs the distortionary cost of carbon taxation are willing to participate in such climate club. That is especially the case for countries in Europe, East Asia and South-East Asia, like China, which trade internationally a large share of goods production, and have hence large gains from trade. Absent tariff retaliation, free-riding prevails over the cost of climate actions, as discussed in Nordhaus (2015). However, if moderate tariffs spur participation for low carbon tax, this incentive effect vanishes quickly as the carbon tax increases and larger emissions reduction are required. The gains from trade are bounded – and small for some countries like Middle-East and Russia – and therefore, there is a limit to what carbon policy can be achieved.

[2]The optimal policy problem with limited instrument is treated extensively in Bourany (2024) in a large class of climate-macroeconomic models. In the present paper, I draw a particular emphasis on international trade and leakage effects, a novel channel that needs to be accounted for in optimal carbon taxation.

Additional policy instruments – such as transfers with a "loss and damage" fund, or fossil-fuel-specific tariffs – improve the climate agreements and increase the carbon tax closer to the second-Best allocation. Indeed, these two instruments addresses two channels to incentivize participation. First, redistributing part of revenues from the carbon tax to poorer economies like South-Asia and Africa – who consume less fossil fuel per capita – improve their welfare much more than the loss incurred by the richer economies of North America, Europe and East-Asia. Second, fossil-fuel-specific tariffs have strong effects on the energy rents of oil-exporting countries. This increases the retaliatory power of the climate club and is more influential to promote participation.

Lastly, I compare how these results on the optimal agreement can change depending on the impact of climate change or the gains from trade. First, I change the damage function and follow the specification of Weitzman (2009), which features larger curvature in temperature warming. This raises the cost of climate change, especially for very warm countries, increases the optimal carbon tax, but also amplifies free-riding incentives. Second, I change elasticity of substitution across goods, which decreases the gains from trade. This reinforces the trade leakage effects and dampens the power of trade instruments as a policy channel for participation. Both reasons lower the optimal carbon tax that can be achieved with an agreement. In this context, additional instruments like transfers or fossil-fuel-specific tariffs are particularly important to broaden participation.

Literature

This works relates to a large literature on the economics of climate change and bridges a gap with both the international trade policy and the game theoretical literature. First, I contribute to the debate on the formation of Climate Club, following the pioneering contribution of Nordhaus (2015). The implementation of climate policy suffers from a free-riding problem and Nordhaus proposed a simple framework to evaluate the principle of issue linkage, i.e. linking the enforcement of a climate policy with trade tariffs. He shows with the C-DICE model that for different – exogenously set – carbon prices and tariffs rates, we can achieve varying participation to a climate club. With low carbon price – up to $25\$/tCO_2$ – and high tariffs – above 10%, the climate club can achieve a club with all the 15 regions he considers.

I depart from Nordhaus' Climate Club framework in three directions. First, I show that when a Social Planner chooses endogenously and optimally both the carbon tax, the tariffs and the club members, we observe an intensive margin - extensive margin tradeoff. Lower tax and higher tariffs increase participation, and conversely. Second, I depart from the C-DICE model that use ad-hoc functions for the carbon abatement – inspired from DICE – and the gain from trade and costs of tariffs – a quadratic approximation of the results of Ossa (2014). I show that modeling the energy market – both with heterogeneity in demand and supply of fossil energy – and trade in goods, accounting for leakage effects and terms-of-trade manipulation, highlight the tradeoff between the cost of carbon taxation and the cost of tariffs. In particular, in this micro-funded setting, gains from trade are bounded, which makes some countries unwilling to join an agreement, if the loss from phasing out fossil fuels is too large, and this *for any tariffs*. Third, I model the cost of climate on production as endogenous to policy, which makes the optimal carbon tax account for redistributive effects through income inequality, trade leakage and energy markets.

Farrokhi and Lashkaripour (2024) also study how climate policy can be conducted with trade instruments. They solve for the optimal trade policy in a rich multi-industry trade model, inspired by Copeland and Taylor (2004), and show that unilateral policy accounts for carbon leakage when setting tariffs. In this setting, they explore the sequential construction of a climate club, where European Union starts a coalition, implements the unilaterally optimal trade-climate policy and iteratively grows the participation to the club. In contrast, I show how should the club *design* the trade-climate policy *strategically* to spur participation. My framework also incorporates several redistribution channels absent from their framework, related to non-linear damage, making the cost of climate change endogenous to policy, or inequality across countries that create differences between policies maximizing output, reducing emissions and improving welfare.

This project lies at the intersection of three literatures, one on trade policy, one the game-theoretical aspects of climate policy cooperation, and one macroeconomic models of climate change,

First, the interdependence between climate, environmental and trade policies is explored extensively in Kortum and Weisbach (2021), Barrett (2001), Bohringer et al. (2016), Bohringer et al. (2012) or Hsiao (2022).These articles explore the differences between unilateral policies implemented at the country level and the potential for climate cooperation using trade policies. Other articles in this trade literature explore the underpinnings of optimal trade policies, e.g. Costinot et al. (2015), Ossa (2014), Adao et al. (2023), Antras et al. (2024), more specifically the choice of trade tariffs for different objectives, like terms of trade manipulation for example. I show how these policy instruments can be used for issue linkage and climate policy.

Moreover, I also borrow from the theoretical literature on climate cooperation, with classical references such as Barrett (1994), Harstad (2012), Barrett (2003), Barrett (2013), Nordhaus (2015) or the older literature collected in Batabyal (2000) or summarized in Maggi (2016). There is also a large literature on dynamic games and coalition formation games, that focus on the building of agreements, either through coordination games or through bargaining procedures, or summarized in Ray and Vohra (2015), or Okada (2023) more recently. Iverson (2024) and Hagen and Schneider (2021) are more recent references in static settings, exploring the stability result and the set of supportable climate coalitions with different feature of climate clubs, where trade policies are crucial. Similarly, Nordhaus (2021), Harstad (2023), or Maggi and Staiger (2022) study those questions as well as other dynamic features, such as technical change, the path of climate dynamics or intertemporal decision-making. I draw inspiration from many of these references. I allow the trade framework I study to be extended to dynamic settings, and I explore the dynamic implications of climate agreement in the near future.

Third, I also draw heavily on a more quantitative literature on the macroeconomic implications of climate change and carbon policy. Indeed, in the continuity of Bourany (2024), I show that the optimal carbon policy should account several general equilibrium channels, as well as macroeconomic dynamics – in the spirit of IAMs. Starting from a static version of the classical DICE/RICE models, c.f. Nordhaus and Yang (1996), Barrage and Nordhaus (2024), I study an extension with optimal fossil fuel taxation, as in Golosov et al. (2014) and with heterogeneous countries/regions, c.f. Krusell and Smith (2022), Cruz and Rossi-Hansberg (2024, 2022), Kotlikoff, Kubler, Polbin, Sachs and Scheidegger (2021), Kotlikoff, Kubler, Polbin and Scheidegger (2021).

When the policy instruments are limited – as in our setting we only consider one uniform level of carbon and penalty tariffs against non-members and no transfer instruments – we need to change endogenously the choice of these instruments, like Hassler et al. (2021), Belfiori et al. (2024), or Douenne et al. (2023), in the case of climate policy, Davila and Walther (2022) or Chari et al. (2023) in more general cases. This follows a large literature on optimal policy in heterogeneous agents models, c.f. Bhandari et al. (2021*a*,*b*), Le Grand et al. (2024) or Davila and Schaab (2023) among many others.

2 An Integrated Assessment Model with inequality and trade

I build a climate-economy model – also called Integrated-Assessment Model (IAM) – that incorporate various dimensions of heterogeneity influencing the incentives of individual countries to join climate agreements. This framework is the simplest model that includes both climate externality, a non-trivial energy market for fossil energy, and a realistic trade structure that reproduces the leakage effects of taxation.

We study a static economy with I countries indexed by $i \in \mathbb{I}$, each with population[3] $\mathcal{P}_i$. Each country is composed of five agents: (i) a representative household that consumes the final goods, (ii) a final-good firm that produces using labor and energy, (iii-v), three energy firms: (iii) a fossil energy firm that extract oil and gas, (iv) a firm producing coal energy, and (v) a firm producing renewable/non-carbon energy. Moreover, each country has a government that sets taxes and tariffs. In the next section, we will develop in detail the choice of those policy instruments considered in the design of the climate agreement.

2.1 Household problem

The representative household in country i imports from country $j \in \mathbb{I}$ and consumes the quantity c_i. We consider an Armington structure, c.f. Anderson (1979), Arkolakis, Costinot and Rodriguez-Clare (2012), where each country produces its own variety. The utility of consumption has a structure with Constant Elasticity of Substitution (CES) θ over goods from different countries.

$$\mathcal{U}_i = \max_{\{c_{ij}\}} u\big(\{c_{ij}\}_j\big) = u(c_i) \qquad\qquad c_i = \Big(\sum_{j\in\mathbb{I}} a_{ij}^{\frac{1}{\theta}} c_{ij}^{\frac{\theta-1}{\theta}}\Big)^{\frac{\theta}{\theta-1}} \tag{1}$$

where a_{ij} are the preference of country i on the good purchased from country j, which also include the home-bias a_{ii}.[4] They also earn labor income and energy rent, and the budget constraint writes:

$$\sum_{j\in\mathbb{I}} c_{ij}\,(1+\mathrm{t}_{ij}^{b})\tau_{ij}\mathrm{p}_j = w_i\ell_i + \pi_i^f + \mathrm{t}_i^{ls} \tag{2}$$

where w_i is the wage rate, ℓ_i the exogenous labor supply, π_i^f the profit earned from the ownership of the energy firms and t_i^{ls} the lump-sum transfer received from the government. On the expenditure side, the household in i imports quantities c_{ij} from j, purchased at price p_j, and subject to iceberg cost τ_{ij} and to trade-tariffs $1+\mathrm{t}_{ij}^b$. The choice of trade policy will be made explicit below.

The optimal consumption choice of the household yields the following quantities and Arm-

[3]Countries are heterogeneous in size $\mathcal{P}_i$ and all the economic variables are expressed per "effective"-capita. For example, y_i or e_i^f are final output and fossil energy use respectively, and $\mathcal{P}_i y_i$ and $\mathcal{P}_i e_i^f$ represent the total quantities produced/consumed in the country. We allow for population and TFP growth in the dynamic climate model and in the dynamic version of this framework

[4]We assume that preferences $\{a_{ij}\}$ and iceberg trade costs $\{\tau_{ij}\}$ are policy-invariant, in particular, they are not sensitive to price changes and tariffs.

ington trade shares:

$$
\begin{aligned}
c_{ij} &= a_{ij} c_i \Big(\frac{(1+\mathrm{t}^b_{ij})\tau_{ij}\mathrm{p}_j}{\mathbb{P}_i}\Big)^{-\theta} \\
s_{ij} \equiv \frac{c_{ij} p_{ij}}{c_i \mathbb{P}_i} &= a_{ij} \frac{((1+\mathrm{t}_{ij})\tau_{ij}\mathrm{p}_j)^{1-\theta}}{\sum_k a_{ik}((1+\mathrm{t}_{ik})\tau_{ik}\mathrm{p}_k)^{1-\theta}}
\end{aligned}
\tag{3}
$$

where $p_{ij} = (1+\mathrm{t}^b_{ij})\tau_{ij}\mathrm{p}_j$ is the effective price for variety from country j sold in country i, and $\mathbb{P}_i$ is the price index of country i:

$$
\mathbb{P}_i = \Big(\sum_{k\in\mathbb{I}} a_{ik}((1+\mathrm{t}_{ik})\tau_{ik}\mathrm{p}_k)^{1-\theta}\Big)^{\frac{1}{1-\theta}}
$$

As a result, we summarize the budget as $c_i\mathbb{P}_i = \sum_{j\in\mathbb{I}} c_{ij}\,(1+\mathrm{t}^b_{ij})\tau_{ij}\mathrm{p}_j$, and the per-capita welfare of country i is summarized with the indirect utility as the income discounted by the price level:

$$
\mathcal{U}_i = u(c_i) = u\Big(\frac{w_i\ell_i + \pi^f_i + \mathrm{t}^{ls}_i}{\mathbb{P}_i}\Big) \tag{4}
$$

2.2 Final good firm problem

The final good producer in country i is producing competitively the domestic variety at price p_i. The firm solves the following maximization of profits:

$$
\max_{\ell_i, e^f_i, e^c_i, e^r_i} \ \mathrm{p}_i\, \mathcal{D}_i(\mathcal{E})\, z_i\, F(\ell_i, e^f_i, e^c_i, e^r_i) - w_i\ell_i - (q^f + \xi^f \mathrm{t}^\varepsilon_i)e^f_i - (q^c_i + \xi^c \mathrm{t}^\varepsilon_i)e^c_i - q^r_i e^r_i
$$

where the production function $\bar{y}_i = F(\ell_i, e^f_i, e^c_i, e^r_i)$ is Constant Return to Scale and concave in all inputs, and uses labor ℓ_i, at wage w_i, fossil energy e^f_i purchased at price q^f, coal e^c at price q^c_i and renewable energy e^r_i at price q^r_i. Energy from oil-gas e^f_i and coal e^c_i differs from renewable in the sense that emits greenhouse gases, with respective carbon concentration ξ^f and ξ^c, as we will see in the next section 2.4. As a result, there is a motive for taxing oil, gas and coal energy with the carbon tax t^ε.

The productivity of the domestic good firm $y_i = \mathcal{D}_i(\mathcal{E})\, z_i\, \bar{y}_i$ can be decomposed in two terms. First, the TFP residual z_i represents productivity as well as institutional/efficiency differences between countries. Invariant to prices and policy, this technology wedge explains the existence of income inequalities across countries. This translates into differences in consumption that create redistribution motives for taxation policy.

The second difference in productivity comes from the climate externality summarized by the net-of-damage function $\mathcal{D}_i(\mathcal{E})$, for world emissions $\mathcal{E}$. This function is a reduced-form representation of the climate system and the damage from temperature increase. It is country-specific due to differences in the vulnerability and costs of climate change. In the quantification section, we detail how we calibrate this function for each country i.

The firm input decisions solve the optimality conditions, where we define the marginal product of an input x as $MPx_i \equiv \mathcal{D}(T_i)\, z_i F_x(\ell_i, e^f_i, e^c_i, e^r_i)$ for $x \in \{\ell_i, e^f_i, e^c_i, e^r_i\}$, for example in the case of oil and gas e_i^f:

$$\mathrm{p}_i \mathcal{D}_i(\mathcal{E})\, z_i\, F_{e^f}(\ell_i, e_i^f, e_i^c, e_i^r) =: \mathrm{p}_i MPe_i^f = q^f + \xi^f \mathrm{t}^\varepsilon \tag{5}$$

and similarly for other inputs $x \in \{\ell_i, e_i^c, e_i^r\}$, with $\mathrm{p}_i MPx_i = q^x$. Moreover, the private decision of the firms does not internalize the climate externality of its own fossil-fuel energy use, except for the carbon tax t^ε.

2.3 Energy markets

The final-good firm is consuming three kind of energy sources – oil-gas, coal or renewable (non-carbon) – which are supplied by three energy firms in each country. Oil-gas are traded internationally, and countries can be exporters or importers. Coal and renewable are both traded locally, an empirically relevant assumption given the substantial trade cost in the international transfers of electricity.

2.3.1 Fossil firm

In each country $i \in \mathbb{I}$, a competitive energy producer extracts fossil fuels – oil and gas – e_i^x and sells it to the international market at price q^f. The energy is extracted at convex cost $\mathcal{C}_i^f(e_i^x)$, where the convex costs are paid in the unit of the consumption bundle of the household.[5]. The energy firm's profit maximization solves:

$$\mathcal{P}_i \pi_i^f = \max_{e_i^x} q^f e_i^x - \mathcal{C}_i^f(e_i^x)\mathbb{P}_i \tag{6}$$

where $\mathcal{P}_i \pi_i^f$ is the total energy rent of country i. Since the extraction costs are convex, the production function has decreasing return to scale[6], and hence, even with competitive firms, taking the fossil price as given, a positive energy rent exists. Moreover, for the sake of simplicity, we do not consider that energy firms have market power in the setting of energy prices – for example in the case of OPEC – even though this framework could easily allow for such extension. Any sources of misallocation – in the sense of Hsieh and Klenow (2009) – is accounted for in the calibration of the cost function $\mathcal{C}_i^f(\cdot)$ as we see in the quantification section.

Naturally, the optimal extraction decision follows from the optimality condition:

$$q^f = \mathcal{C}_i^{f\prime}(e_i^x)\mathbb{P}_i \tag{7}$$

which yields the implicit function $e^{x\star} = e^x(q^f/\mathbb{P}_i) = \mathcal{C}_i^{f\prime\,-1}(q^f/\mathbb{P}_i)$. Finally, the energy rent comes from fossil firms' profits $\pi^f(q^f, \mathbb{P}_i) = q^f e^x(q^f/\mathbb{P}_i) - \mathcal{C}_i^f\left(e^x(q^f/\mathbb{P}_i)\right)\mathbb{P}_i > 0$ and depends on the marginal costs as well as the elasticity $\nu_i = \frac{\mathcal{C}_i^{f\prime\prime}(e^x)}{\mathcal{C}_i^{f\prime}(e^x)e^x}$.

[5]This allows to account for international inputs in goods and services for building capital for resources extraction

[6]We can also define a fossil production function with inputs x_i^f such that $e^x = g(x_i^f)$ and profit $\pi = q^f g(x) - x\mathbb{P}_i$ instead of $\pi = q^f e^x - \mathcal{C}(e^x)\mathbb{P}_i$, in which case $g(x) = \mathcal{C}^{-1}(x)$

As we will see below, the profit $\pi^f(q^f, \mathbb{P}_i)$ and its share in income $\eta_i^{\pi f} = \frac{\pi_i{}^f}{y_i \mathrm{p}_i + \pi_i{}^f}$ are key indicators for the vulnerability of a country to carbon taxation. Indeed, reducing carbon emission and the phasing out of fossil fuels reduces demand and price q^f and hence affect the welfare of large oil and gas producers.

2.3.2 International fossil energy markets

In the previous sections, we outlaid both the demand and supply of the fossil energy market. We consider that oil and gas are traded frictionlessly on international markets.[7] The market clears such that:

$$E^f = \sum_{i \in \mathbb{I}} \mathcal{P}_i e_i^f = \sum_{i \in \mathbb{I}} e_i^x \tag{8}$$

In particular, countries have different exposure to energy markets, as importers or exporters $e_i^x - e_i^f$. First, larger, richer and more productive countries use larger quantities of energy and tend to have higher energy share $\frac{q^e e_i}{\mathrm{p}_i y_i}$. Moreover, countries i that export final goods and are central in international trade networks – due to low iceberg cost τ_{ki} or high preferences a_{ki} for all $k \in \mathbb{I}$ – would have higher prices p_i and hence use more energy.

Second, countries export energy if their cost of extraction is low $\mathcal{C}_i'$ which can represent either (i) low marginal cost of production per unit of fossil reserve, (ii) large reserves of fossil fuels lowering the cost of the endowment or (iii) institutional factors that allow for higher production. These factors will be crucial in the participation of countries in climate agreements.

2.3.3 Coal firm

The final good firm uses coal. We differentiate coal for other fossil fuels like oil and gas, since coal production typically does not generate large energy rent for producing countries, which consume a large fraction of it locally. We make this empirically-grounded assumption that the supply of coal is entirely local at country-level i.

The production $\bar{e}_i^c$ from the representative clean energy firm is Constant Return to Scale and uses final good inputs, paid in the consumption bundle at price $\mathbb{P}_i$.

$$\pi_i^c = \max_{e_i^c} q_i^c \bar{e}_i^c - \mathcal{C}_i^c \mathbb{P}_i$$

where $\mathcal{C}_i^c$ is now simply a constant, as implied by constant return (CRS). This implies that there is no coal profit in equilibrium, i.e. $\pi_i^c = 0$. This is motivated by empirical evidence that even the largest coal producers never generate coal rents above 1%. As a result, the price of renewable and

[7]For the sake of simplicity, I refrain from considering a general Armington structure, where fossil demand combines varieties from different sources $e_i^f = \left(\sum_j (e_{ij}^f)^{\frac{\Theta-1}{\Theta}}\right)^{\frac{\Theta}{\Theta-1}}$. I make the simplifying assumption that fossil fuels produced in different countries are not distinguishable – crude oil from Nigeria, Saudi Arabia or Russia are not differentiated varieties – and consider the limiting case $\Theta \to \infty$

the market clearing write:

$$q_i^c = \mathcal{C}_i^c \mathbb{P}_i \qquad\qquad \bar{e}_i^c = e^c \tag{9}$$

This implies – for a given price index of inputs $\mathbb{P}_i$ – an elastic supply curve for coal energy, something we observe in practice as coal production is easily scalable in response to oil and gas price fluctuations.

2.3.4 Renewable, non-carbon, firm

The final good firm also uses renewable and other low-carbon energy sources, such as solar, wind or nuclear electricity. This provides a way of substituting away from fossil fuel in the production function $F(\ell, e^f, e^c, e^r)$. As mentioned above, the demand for renewable energy e_i^r follows from the First-Order Condition $\mathrm{p}_i MPe^r = q_i^r$.

The supply of renewable energy is local at country-level i. This assumption follows from the fact that electricity is rarely traded across countries – and if it is, it only suggests temporary differences in electricity production due to intermittency, rather than large structural imbalances. The production $\bar{e}_i^r$ from the representative clean energy firm is also Constant Return to Scale and uses final good inputs, paid in the consumption bundle at price $\mathbb{P}_i$.

$$\pi_i^r = \max_{e_i^r} q_i^r \bar{e}_i^r - \mathcal{C}_i^r \mathbb{P}_i$$

where $\mathcal{C}_i^r$ is a constant, again implied by constant return (CRS), resulting in zero profit $\pi_i^r = 0$. As a result, the price of renewable and the market clearing write

$$q_i^r = \mathcal{C}_i^r \mathbb{P}_i \qquad\qquad \bar{e}_i^r = e^r \tag{10}$$

The same elastic supply curve result applies here. This is a stronger assumption in the context of renewable energy. Indeed, in the short run renewable energy requires investments in capacity, implying a steep /inelastic supply curve, especially considering the intermittency problems of wind and solar, c.f. Gentile (2024). However, in the long-run, technological progress and learning-by-doing create positive externality decreasing substantially the cost of clean energy, which results a decreasing supply-curve, c.f. Arkolakis and Walsh (2023). We take the intermediary conservative assumption that the supply curve is flat, and explore robustness of this assumption in future extensions.

2.4 Climate system

Carbon emissions released from the burning of fossil fuels creates a climate externality as they feed back into the atmosphere, increasing temperature, and affecting damages.

We describe the damage function $\mathcal{D}_i(\mathcal{E})$ affecting country i productivity as a reduced-form summary of the impact of climate change. We develop a standard dynamic climate system that can be summarized in a static form in a simple way. It express the mapping from (i) emissions $\mathcal{E}$ to a path a atmospheric carbon concentration $\mathcal{S}_t$, (ii) from carbon concentration to a path of global and local temperatures T_{it}, and then from temperature to damage $\mathcal{D}_i(T_{it})$, and (iv) finally summarizes it in present discounted value.

First, the static model represents stationary decisions on energy choices taken "once and for all". These yearly emissions from fossil fuels sums up to

$$\mathcal{E} = \sum_{i \in \mathbb{I}} \mathcal{P}_i (\xi^f e_i^f + \xi^c e_i^c)$$

where ξ^f and ξ^c represents the carbon concentration of oil-gas and coal respectively. This leads to a constant[8] path of emissions $\mathcal{E}_t = \mathcal{E}, \forall t$. They represent trajectories of emissions or "pledges" taken in the context of climate agreement policy.

Second, we consider a dynamic system – in continuous time – for carbon concentration in the atmosphere:

$$\dot{\mathcal{S}}_t = \zeta_t \mathcal{E}_t - \delta_s \mathcal{S}_t \qquad\qquad \mathcal{S}_{t_0} = \mathcal{S}_{2023}$$

where δ_s is the rate of decay of carbon out of the atmosphere, which is typically small for typical calibrations. To make the carbon concentration bounded and non-exploding – given the constant path of emissions – I follow Krusell and Smith (2022) by assuming that part of emissions $\mathcal{E}_t$ is abated via carbon capture and storage (CCS) modeled by the exogenous parameter ζ_t. The share of emissions abated raised to 100% in the long-run, implying that $\zeta_t \to_{t\to\infty} 0$. Increasing CCS allows to reach net-zero in several centuries, stabilizing cumulative carbon emissions and temperature.

Third, we consider a linear relationship between the cumulative CO_2 emissions $\mathcal{S}$, and global temperature $\mathcal{T}$ anomaly compared to preindustrial level.

$$\mathcal{T}_t = \chi \mathcal{S}_t = \chi \Big(\mathcal{S}_{t_0} + \int_{t_0}^{\infty} e^{-\delta_s (t-t_0)} \zeta_t \mathcal{E}_t dt \Big)$$

where χ is the climate sensitivity parameters, i.e. how much warming does a ton of CO_2 cause, and where e_i^f are measured in carbon units, and the $\mathcal{S}_0$ is the initial stock of carbon before all the policy decision are made – i.e. in 2020. This specification is rationalized by a large climate-sciences literature that shows that both historical data and a large class of climate model display an approximately linear relationship between $\mathcal{S}$ and $\mathcal{T}$, as is shown is the following figure:

Fourth, we consider linear relation between global temperature and local temperature, which

[8]In the quantitative section, we also consider country-specific growth rates for TFP $\bar{g}_i$ and population n_i. This leads to path of emissions that writes as follow:

$$\mathcal{E}_t = \sum_{i \in \mathbb{I}} \mathcal{P}_i e^{(\bar{g}_i + n_i)t} (\xi^f e_i^f + \xi^c e_i^c)$$

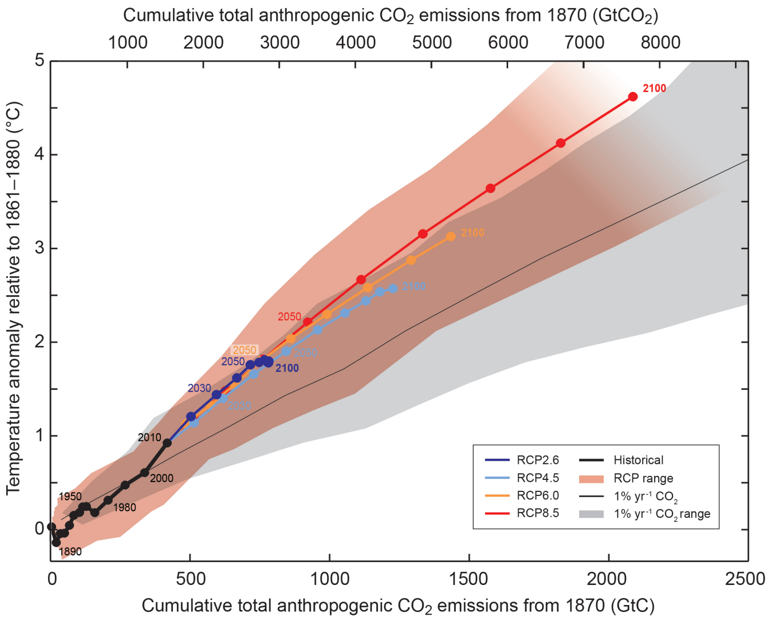


Figure 1: Linearity – Cumulative emissions and temperature

affect the local damages:

$$T_{it} = \bar{T}_{i0} + \Delta_i \mathcal{T}_t = \bar{T}_{i0} + \Delta_i \chi \mathcal{S}_t$$

where Δ_i is a linear pattern scaling parameter that depends on geographical factor such as albedo or latitude. In the quantification section, this pattern scaling is estimated regressing local temperature on global temperature.

Fifth, we consider a period damage function $\mathcal{D}(T_{it} - T_i^\star)$ where $T_i^\star$ is the "optimal" temperature for country i. The function $\mathcal{D}(\hat{T})$ is a reduced-form representation of the economic damage to productivity. In our baseline quantification, damage is considered quadratic as in standard Integrated Assessment Models. This methodology follows Krusell and Smith (2022), Kotlikoff, Kubler, Polbin, Sachs and Scheidegger (2021) and Burke et al. (2015). Such damage create winners and losers: countries that are substantially warmer than a target temperature $T_i^\star$ will be extremely affected by increases in temperature due to climate change. In contrast, regions with negative $T_{it} - T_i^\star$ will benefit – at least in the short-run – from a warmer climate. I provide a slight deviation to the above articles by assuming that the target temperature $T_i^\star$ might be different across countries: an already warm regions have different adaptation costs compared to a country which is historically cold. As a result, the target temperature $T_i^\star = \alpha T^\star + (1-\alpha)\bar{T}_{i0}$ can be more or less tilted toward historical temperature.

However, since this damage function has considerable uncertainty, we test the sensitivity of the results to different functional forms in the later section.

Finally, to obtain a reduced-form static damage function $\mathcal{D}_i(\mathcal{E})$ we summarize the future costs of climate change in present-discounted value

$$\mathcal{D}_i(\mathcal{E}) = \int_{t_0}^{\infty} e^{-\rho t}\mathcal{D}\big(T_{it} - T_i^{\star}\big)dt$$

where ρ is the household discount factor.

We see that despite the model being static we can incorporate climate system dynamics[9] as in standard Integrated Assessment Models. The future damages are summarized in the stationary equilibrium and affect the Social Cost of Carbon and the Pigouvian level of carbon taxation, c.f. section 5.1

2.5 Equilibrium

To close the model, we need determine the final good prices for each country p_i and we consider the market clearing for each good i

$$\begin{aligned} y_i &= \sum_{k\in\mathbb{I}} \tau_{ki} c_{ki} + \sum_{k\in\mathbb{I}} \tau_{ki}(x_{ki}^f + x_{ki}^c + x_{ki}^r) \\ \mathrm{p}_i \underbrace{y_i}_{=\mathcal{D}_i(\mathcal{E})z_iF(\cdot)} &= \sum_{k\in\mathbb{I}} \frac{s_{ki}}{1+\mathrm{t}_{ki}^b}\left(\mathrm{p}_k y_k + q^f(e_k^x - e_k^f) + \mathrm{t}_k^{ls}\right) \end{aligned} \tag{11}$$

where x_{ki}^f, x_{ki}^c and x_{ki}^r are the good inputs used by country k and imported from country i to produce fossil and renewable energy respectively.

To summarize, the competitive equilibrium of this economy is defined as follow:

Definition. Competitive equilibrium (C.E.):
For a set of policies $\{\mathrm{t}_i^{\varepsilon}, \mathrm{t}_{ij}^b, \mathrm{t}_i^{ls}\}_i$ across countries, a C.E. is a set of decisions $\{c_{ij}, e_i^f, e_i^c e_i^r, e_i^x, \bar{e}_i^c, \bar{e}_i^r\}_{ij}$, and prices $q^f, \{\mathrm{p}_i, w_i, q_i^c, q_i^r\}_i$ such that
(i) Household choose consumption $\{c_{ij}\}_{ij}$ maximizing utility eq. (1) s.t. budget constraint eq. (2), giving trade shares eq. (3)
(ii) Final good firm choose inputs $\{\ell_i, e_i^f, e_i^r\}_i$ to maximize profit, resulting in decisions eq. (5)
(iii) Fossil energy firm maximize profit eq. (6) and extract/produce $\{e_i^x\}_i$ given by eq. (7)
(iv) Renewable and coal energy supplies $\{\bar{e}_i^c, \bar{e}_i^r\}$ is given respectively by eq. (9) and eq. (10) by firms maximizing profit
(v) Energy market clear for fossils as in eq. (8) and for coal and renewable in eq. (9) and eq. (10)
(vi) Good market clear for final good for each country as in eq. (11)

[9] It would not be computationally to incorporate a more realistic climate system as in state-of-the-art IAM or Dietz et al. (2021) or Folini et al. (2024), for example with a 3 atmospheric blocks and 2 oceanic blocks.

3 The Optimal Agreement Design with endogenous participation

Because of unequal exposure to climate change and carbon policy, countries have different incentives in enforcing climate policy, exacerbating the free-riding problem. Therefore, the optimal carbon tax needs to account for endogenous participation. Designing a climate agreement reveals a trade-off between an intensive-margin – associated with the choice of the policy instruments – and an extensive margin – related to the extent of participation in the agreement.

3.1 Agreement design and participation constraints

The social planner solves a Ramsey problem, choosing the optimal agreement, which boils down to a carbon tax, retaliatory tariffs on non-participants, and a set of countries participating in the agreement, subject to participation constraints. We first design the set of climate agreement considered and then define the planner objective.

Definition – climate agreements

A climate agreement is a set $\{\mathbb{J}, \mathrm{t}^\varepsilon, \mathrm{t}^b\}$, i.e. a coalition, a carbon tax and a tariff, with $\mathbb{J} \subseteq \mathbb{I}$ countries and a competitive equilibrium ***C.E.*** such that:

- Countries $i \in \mathbb{J}$ are subject to a carbon tax t^ε on fossil energy e_i^f
- Countries can leave the climate agreement: If j exits the agreement, club members $i \in \mathbb{J}$ charges uniform tariffs $\mathrm{t}_{ij}^b = \mathrm{t}^b$ on the final good from j.
- Countries inside the club $i, j \in \mathbb{J}$ benefit from free-trade $\mathrm{t}_{ij}^b = 0$.
- Countries outside the club $k, \ell \notin \mathbb{J}$ benefit from free-trade $\mathrm{t}_{k\ell}^b = 0$. This assumption will be relaxed in section 5.2
- All countries – member as well as non-member – still trade in fossil (oil-gas) energy at international price q^f. This assumption will be relaxed in section 7.1

We keep the number of policy instruments $\mathbf{t} = \{\mathrm{t}^\varepsilon, \mathrm{t}^b\}$ considered in the agreement voluntarily small. This is consistent with the idea behind deviations of the Coase theorem: when bargaining over policy instruments is associated with transaction costs, a negotiation between n parties – $\mathbb{J}$ countries here – "can be prevented from attaining a socially desirable outcome", c.f. Weitzman (2015). For this reason, I refrain for considering climate agreements that bargain over a set of country-specific taxes t_i^ε, or emissions quantity targets ε_i or bilateral tariffs t_{ij}^b, since the bargaining cost would increase at least proportionally – if not exponentially – in the number of countries. The case of individual carbon taxes is analyzed in Bourany (2024).

Participation constraints

Defining indirect utility $\mathcal{U}_i(\mathbb{J}, \mathrm{t}^\varepsilon, \mathrm{t}^b) \equiv u(c_{i(\mathbb{J}, \mathrm{t}^\varepsilon, \mathrm{t}^b)})$ as in section 2.1, we can define participation constraints in two ways, depending on the equilibrium we consider.

1. *Unilateral deviation:* country i can choose to exit the agreement unilaterally. This does not affect the composition of the agreement and the decision of the other members. The participation of country i in the agreement is made if the value from staying in is larger than the value of being outside the agreement

$$\mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \geq \mathcal{U}_i(\mathbb{J}\backslash\{i\}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \qquad \forall\ i \subseteq \mathbb{J} \qquad \text{[Unilateral-Nash PC]} \tag{12}$$

2. *Sub-coalition deviation:* country i can choose to exit the agreement in cooperation with other members of a potential sub-coalition $\hat{\mathbb{J}}$. All these members leave the agreement. The decision of all those countries $i \in \hat{\mathbb{J}}$ to leave is made jointly: the value of being outside is above the value of staying for all $i \in \hat{\mathbb{J}}$. This makes the participation constraints more intricate and write as follow:

$$\mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \geq \mathcal{U}_i(\mathbb{J}\backslash\hat{\mathbb{J}}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \qquad \forall\ i \in \hat{\mathbb{J}}\ \&\ \forall\ \hat{\mathbb{J}} \subseteq \mathbb{J} \qquad \text{[Coalition-Nash PC]} \tag{13}$$

The optimal agreement needs to account for these participation constraints, and be robust to unilateral or sub-coalition deviations.

Welfare criterion and planner's objective

We consider a global social planner maximizing the world welfare:

$$\max_{\mathbb{J},\mathrm{t}^{\varepsilon},\mathrm{t}^b} \mathcal{W}(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) = \max_{\mathbb{J},\mathrm{t}^{\varepsilon},\mathrm{t}^b} \sum_{i \in \mathbb{I}} \mathcal{P}_i \omega_i\, \mathcal{U}_i(\mathbb{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \tag{14}$$

subject to participation constraint – Unilateral Nash, robust to deviation

$$\mathbb{J} \in \mathbb{S}(\mathrm{t}^{\varepsilon}, \mathrm{t}^b) = \left\{\mathcal{J} \mid \mathcal{U}_i(\mathcal{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \geq\ \mathcal{U}_i(\mathcal{J}\backslash\{i\}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b), \quad \forall\ i \in \mathcal{J}\right\} \tag{15}$$

or Coalitional-Nash, robust to sub-coalition $\hat{\mathbb{J}}$ deviations:

$$\mathbb{J} \in \mathbb{C}(\mathrm{t}^{\varepsilon}, \mathrm{t}^b) = \left\{\mathcal{J} \mid \mathcal{U}_i(\mathcal{J}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b) \geq \mathcal{U}_i(\mathcal{J}\backslash\hat{\mathbb{J}}, \mathrm{t}^{\varepsilon}, \mathrm{t}^b), \quad \forall\ i \in \mathcal{J},\ \forall\ i \in \hat{\mathbb{J}}\ \&\ \forall\ \hat{\mathbb{J}} \subseteq \mathcal{J}\right\} \tag{16}$$

where ω_i are the Pareto weights, and $\mathcal{P}_i$ the population size of country i. The social planner seeks to maximizes world welfare, ideally with the goal to fight climate change and solve this global externality. As a result, the planner maximizes the sum over $\mathbb{I}$ instead of over $\mathbb{J}$. In such case, only maximizing the coalition welfare would yield unintended consequence that the optimal climate agreement would be restricted to a subset of rich, cold, high value $\mathcal{U}_i$ who would manipulate terms-of-trade and potentially subsidize fossil fuels. This is obviously not the usual goal of climate agreements, which aim at maximizing the world welfare.

The set of agreement stable under Coalition-Nash resembles the concept of "core" in general equilibrium theory. Both of these sets $\mathbb{S}(\mathrm{t}^{\varepsilon}, \mathrm{t}^b)$, $\mathbb{C}(\mathrm{t}^{\varepsilon}, \mathrm{t}^b)$ could be empty: it is possible that no country find it beneficial to be part of the agreement for a given policy $\mathrm{t}^{\varepsilon}, \mathrm{t}^b$.

Extensive margin vs. intensive margin tradeoff

The problem is mixed between a choice of the policy instruments $\mathrm{t}^{\varepsilon}, \mathrm{t}^{b}$ and the choice of the country subject to participation constraints $\mathbb{J} \in \mathbb{S}(\mathrm{t}^{\varepsilon}, \mathrm{t}^{b})$ or $\mathbb{C}(\mathrm{t}^{\varepsilon}, \mathrm{t}^{b})$. As a result, this reveals an extensive-intensive margin trade-off. Indeed, for a given set of participants $\mathbb{J}$, higher carbon tax t^{ε} and lower tariffs t^{b} increase global welfare. The planner would like to reduce carbon emissions and promote free-trade at the intensive margin to maximize welfare. However, this choice of instruments also affect countries participation: higher taxes t^{ε} and lower tariffs t^{b} reduces incentive for countries to participate. If a country deviate by exiting the agreement, they increase their emissions and international trade is reduced, lowering welfare at the extensive margin. As a result, the planner would like to balance these two countervailing effects. This tradeoff will be analyzed in details in the context of this climate-economy model in section 6.3.

3.2 Optimal design and solution method

This policy problem combines a choice of instruments and a choice of countries and is therefore difficult to solve. I provide two methods to handle the joint optimal policy/combinatorial discrete choice problem.

3.2.1 Framework for the optimal design

We formalize the policy problem under the different participation constraints – Unilateral deviation vs. Coalition deviation – subject to the allocation being a competitive equilibrium. For the sake a notation, we consider a general class of policy instruments $\mathbf{t}$ that encompass carbon tax $\mathrm{t}_i^{\varepsilon} = \mathrm{t}^{\varepsilon}\mathbb{1}_{\{i \in \mathbb{J}\}}$, uniform tariffs on non-members $\mathrm{t}_{ij}^{b} = \mathrm{t}^{b}\mathbb{1}_{\{i \in \mathbb{J}, j \notin \mathbb{J}\}}$ as well as potential additional instruments as analyzed in section 7.

$$\max_{\mathbb{J},\mathbf{t}} \mathcal{W}(\mathbb{J},\mathbf{t}) = \max_{\mathbb{J},\mathbf{t}} \sum_{i \in \mathbb{I}} \mathcal{P}_i \omega_i \, \mathcal{U}_i(\mathbb{J},\mathbf{t})$$
$$s.t. \qquad \mathbb{J} \in \mathbb{S}(\mathbf{t}) \quad or \quad \mathbb{J} \in \mathbb{C}(\mathbf{t})$$

Participation constraints $\mathbb{S}(\mathbf{t})$ or $\mathbb{C}(\mathbf{t})$, as defined in eq. (15) and eq. (16), makes the problem intricate as it limits the instruments the planner can use for each set of countries in the agreements.

I take the following approach: I split the problem into an inner problem and an outer problem. First, the planner chooses the policy instruments $\mathbf{t}$, and then the participation constraints yields a set of possible coalition achievable. If no coalition is achievable, then the welfare for those instruments is $-\infty$.

$$\max_{\substack{\mathbb{J},\mathbf{t} \\ \mathbb{J} \in \mathbb{S}(\mathbf{t})}} \mathcal{W}(\mathbb{J},\mathbf{t}) = \max_{\mathbf{t}} \max_{\mathbb{J} \,|\, \mathbb{J} \in \mathbb{S}(\mathbf{t})} \mathcal{W}(\mathbb{J},\mathbf{t})$$

This separates the difficulty of the problem into an outer policy problem – instruments $\mathbf{t}$ choice – and an inner combinatorial discrete choice problem (CDCP) for coalition $\mathbb{J}$ taking as given the policy $\mathbf{t}$.

We explain in appendix why the opposite approach – solving for the coalition as an outer problem and for policy instruments in the inner problem – is intractable.[10].

In the approach presented here, the outer problem for the choice of instrument $\mathbf{t}$ is solved with a simple grid search since the indirect welfare is now typically discontinuous and non-convex in practice.

$$\max_{\mathbf{t}} \widehat{\mathcal{W}}(\mathbf{t}) \qquad\qquad \widehat{\mathcal{W}}(\mathbf{t}) = \max_{\mathbb{J}\,|\,\mathbb{J}\in\mathbb{S}(\mathbf{t})} \mathcal{W}(\mathbb{J},\mathbf{t})$$

For this reason, we keep the number of instruments small $\mathbf{t} = \{\mathrm{t}^{\varepsilon}, \mathrm{t}^{b}\}$. This aligns with standard principles of parsimony, and the arguments behind deviations of the Coase theorem when bargaining over policy instruments is associated with transaction costs.

3.2.2 Solution methods

I propose two methods to solve for the inner problem, which is still a combinatorial discrete choice problem. Indeed, choosing the optimal choice of countries $\mathbb{J}^{\star}$ out of all the possible combinations $\mathcal{P}(\mathbb{I})$ can be prohibitive numerically. To handle this challenge, I first use an exhaustive search method, and then I propose a squeezing procedure inspired from tools from the trade literature as a more efficient alternative in the unilateral-Nash case. I introduce the problem we are facing first before presenting each method in turn.

The combinatorial discrete choice problem we are facing, for a given policy $\mathbf{t}$, writes:

$$\begin{aligned} &\max_{\mathbb{J}\in\mathcal{P}(\mathbb{I})} \mathcal{W}(\mathbb{J},\mathbf{t}) \\ &s.t. \qquad \mathbb{J}\in\mathbb{S}(\mathbf{t}) \end{aligned}$$

Expressing the Lagrangian of the constrained optimization, with multiplier ν_i for country i's participation, we obtain – with a slight abuse of notation[11] – the problem

$$\max_{\mathbb{J}\in\mathcal{P}(\mathbb{I})} \mathcal{W}(\mathbb{J},\mathbf{t}) + \sum_{i\in\mathbb{J}} \nu_{i,\mathbb{J}} \Big(\mathcal{U}_i(\mathbb{J},\mathbf{t}) - \mathcal{U}_i(\mathbb{J}\backslash\{i\},\mathbf{t}) \Big) =: \max_{\mathbb{J}\in\mathcal{P}(\mathbb{I})} \widetilde{\mathcal{W}}(\mathbb{J},\mathbf{t}) \tag{17}$$

in the case where the participation constraint only consider unilateral deviation[12].

First method: Exhaustive enumeration

First, when the number of countries $I = \#\mathbb{I}$ is small, one obvious yet costly solution is to perform an exhaustive search over $\mathcal{P}(\mathbb{I})$. The idea is to enumerate all the combinations $\mathbb{J}\in\mathcal{P}(\mathbb{I})$, and evaluate

[10] In a few words, in subgame perfect equilibria, it would makes the Lagrange multipliers on the participation constraints ν_i depends not only on the coalition considered $\mathbb{J}$, but all the coalition in every subgame, e.g. $\mathbb{J}\backslash\{i\}$ etc. These multipliers obviously affects the policy choice and makes the problem unsolvable

[11] Since the function $\mathcal{W}(\mathbb{J},\mathbf{t}) = \mathcal{W}(I_1, I_2, \ldots, I_n, \mathbf{t})$ for $I_j = 1$ for $j\in\mathbb{J}$ and 0 otherwise, we see that the objective is not continuous, nor differentiable, nor even convex. The handling of the inequality constraints could not in theory rely on KKT theorem which applies in the $\mathcal{C}^1$ and convex case. However, we can consider that $\nu_{i,\mathbb{J}} = \begin{cases} 0 & \text{if } \mathbb{J}\in\mathbb{S}(\mathbf{t}) \\ +\infty & \text{if } \mathbb{J}\notin\mathbb{S}(\mathbf{t}) \end{cases}$ to make the problem well defined

[12] A longer list of constraints need to be included if we consider coalition-deviations

welfare $\mathcal{W}(\mathbb{J}, \mathbf{t})$. This has evidently a computational cost proportional to $2^{\#\mathbb{I}}$, i.e. the number of potential combinations.

This has however the advantage of considering the participation constraints – including the coalition-robust agreements – "for free". Indeed, it allows to assess if the participation constraints holds both in the case of unilateral-Nash $\mathbb{J} \in \mathbb{S}(\mathbf{t})$ and coalitional-Nash $\mathbb{J} \in \mathbb{C}(\mathbf{t})$, for all sets $\mathbb{J}$. This is feasible because every possible deviation of sub-groups $\hat{\mathbb{J}}$ yields a new agreement $\mathbb{J}' = \mathbb{J} \backslash \hat{\mathbb{J}}$ that is already computed as one of the other coalition $\mathbb{J}' \in \mathcal{P}(\mathbb{I})$. In such case, if one of the participation constraints is violated, the set considered $\mathbb{J}'$ is discarded, i.e. $\nu_{i,\mathbb{J}'} = \infty$, $\mathcal{W}(\mathbb{J}') = -\infty$. In practice, several coalitions can be stable for a given policy $\mathbf{t}$ and the exhaustive search allows to choose the one that maximizes welfare.

In practice, among all the stable coalitions – respecting participation constraints – the one that maximizes welfare is typically the largest one since for a given policy $\mathbf{t} = \{\mathrm{t}^{\varepsilon}, \mathrm{t}^{b}\}$, the larger the coalition, the higher the gains from trade and the gains from reducing emissions[13].

Second method: Squeezing procedure for CDCP with Participation Constraints Second, since full enumeration is costly, I provide an alternative algorithm inspired from the methods used in the trade literature to solve combinatorial discrete choice problems. The additional difficulty that needs to be considered is the presence of participation constraints. In this section, we only consider unilateral deviations. The idea behind this method is greatly inspired by Arkolakis, Eckert and Shi (2023) and Farrokhi and Lashkaripour (2024)

The idea is to build iteratively sets that are lower bound $\underline{\mathcal{J}}$ and upper bound $\overline{\mathcal{J}}$ sets for the optimal coalition $\mathbb{J}$: $\underline{\mathcal{J}}$ is a subset which *includes* all the countries that we know to be part of the optimal set $\mathbb{J}$ and $\overline{\mathcal{J}}$ is a superset, such that it excludes the countries that we know are not part of the optimal set. The set $\overline{\mathcal{J}} \backslash \underline{\mathcal{J}}$ is the set of potential countries. The natural starting point is $\underline{\mathcal{J}} = \varnothing$, $\overline{\mathcal{J}} = \mathbb{I}$.

The squeezing step in standard CDCP is a mapping from $\mathcal{J}$ to members that bring a positive marginal value to the objective $\mathcal{W}(\mathbb{J}) := \mathcal{W}(\mathbb{J}, \mathbf{t})$. The modification needed in our setting with participation constraints is that the country also needs have marginal *individual* value $\mathcal{U}_i(\mathcal{J}) = \mathcal{U}_i(\mathcal{J}, \mathbf{t})$ to be part of the coalition:

$$\Phi(\mathcal{J}) \equiv \left\{ j \in \mathbb{I} \,\middle|\, \Delta_j \mathcal{W}(\mathcal{J}) > 0 \ \&\ \Delta_j \mathcal{U}_j(\mathcal{J}) > 0 \right\} \tag{18}$$

where the marginal values for global welfare and individual welfare is

$$\Delta_j \mathcal{W}(\mathcal{J}) \equiv \mathcal{W}(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{W}(\mathcal{J} \backslash \{j\}, \mathbf{t}) = \sum_{i \in \mathbb{I}} \mathcal{P}_i \omega_i \big(\mathcal{U}_i(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_i(\mathcal{J} \backslash \{j\}, \mathbf{t}) \big)$$

$$\Delta_j \mathcal{U}_j(\mathcal{J}) \equiv \mathcal{U}_j(\mathcal{J} \cup \{j\}, \mathbf{t}) - \mathcal{U}_j(\mathcal{J} \backslash \{j\}, \mathbf{t}) \big)$$

[13]As long as t^{ε} is below the globally optimal carbon tax as we derive it in section 5.1.2

The iterative procedure build the lower bound $\underline{\mathcal{J}}$ and upper bound $\overline{\mathcal{J}}$ by successive application of the squeezing step.

$$\underline{\mathcal{J}}^{(k+1)} = \Phi(\underline{\mathcal{J}}^{(k)}) \qquad\qquad \overline{\mathcal{J}}^{(k+1)} = \Phi(\overline{\mathcal{J}}^{(k)}) \tag{19}$$

Under some conditions – complementarity, c.f. below – this sequential procedure yields two sets $\underline{\mathcal{J}}$ and $\overline{\mathcal{J}}$ such that $\underline{\mathcal{J}} \subseteq \mathbb{J} \subseteq \overline{\mathcal{J}}$. In some cases $\underline{\mathcal{J}} = \overline{\mathcal{J}} = \mathbb{J}$ which gives the optimal coalition. If not, with $\overline{\mathcal{J}} \backslash \underline{\mathcal{J}} = \mathcal{J}^{pot}$, we find the optimal coalition by searching exhaustively over all coalitions in:

$$\mathcal{J}^{rem} = \left\{ \mathcal{J} \,\middle|\, \mathcal{J} = \underline{\mathcal{J}} \cup \hat{\mathcal{J}}, \text{ with } \hat{\mathcal{J}} \in \mathcal{P}(\mathcal{J}^{pot}) \right\}$$

Applicability of the squeezing procedure

From the combinatorial discrete choice literature, Arkolakis et al. (2023), we know that the squeezing procedure applies in cases where the model exhibit "complementarity" or single-crossing differences in choices.

Indeed, we say that the objective $\mathcal{W}(\mathcal{J})$ obeys the property of *single crossing differences in choice* (SCD-C) from below if:

$$\Delta_j \mathcal{W}(\mathcal{J}) \geq 0 \quad \Rightarrow \quad \Delta_j \mathcal{W}(\mathcal{J}') \geq 0 \qquad \text{for } \mathcal{J} \subset \mathcal{J}' \quad \& \quad j \in \mathbb{I}$$

A simple sufficient condition for SCD-C, from below to be respected is that the marginal value of the objective is monotone in the set $\mathcal{J}$, also called "complementarity":

$$\Delta_j \mathcal{W}(\mathcal{J}) \leq \Delta_j \mathcal{W}(\mathcal{J}') \qquad \text{for } \mathcal{J} \subseteq \mathcal{J}' \qquad \& \quad j \in \mathbb{I}$$

Theorem (Arkolakis et al. (2023)) The SCD-C from below is *sufficient* for the application of squeezing algorithm to yield $\underline{\mathcal{J}} \subseteq \mathbb{J} \subseteq \overline{\mathcal{J}}$ in standard CDCPs.

In our setting, considering participation constraints requires to adjust the welfare objective, from $\mathcal{W}(\mathbb{J})$ to $\widetilde{\mathcal{W}}(\mathbb{J})$ as in eq. (17). In this context, the single crossing differences in choice with participation constraints (SCD-C, PC) takes an intricate form, which we detail in appendix [APPENDIX REF HERE]. The following condition is sufficient for (SCD-C, PC) and provides intuitions on the trade-offs at play in the construction of the optimal coalition:

$$\begin{cases} \Delta_j \mathcal{W}(\mathcal{J}, \mathbf{t}) \;\leq \Delta_j \mathcal{W}(\mathcal{J}', \mathbf{t}) \\ 0 \leq \Delta_i \mathcal{U}_i(\mathcal{J} \cup \{j\}, \mathbf{t}) \;\leq \Delta_i \mathcal{U}_i(\mathcal{J}' \cup \{j\}, \mathbf{t}) \qquad \forall\, i \in \mathcal{J} \cup \{j\} \;\&\; i \in \mathcal{J}' \cup \{j\} \\ 0 \leq \Delta_i \mathcal{U}_i(\mathcal{J}, \mathbf{t}) \;\leq \Delta_i \mathcal{U}_i(\mathcal{J}', \mathbf{t}) \qquad \forall\, i \in \mathcal{J} \& i \in \mathcal{J}' \end{cases} \tag{20}$$

or

$$\begin{cases} 0 \leq \Delta_i \mathcal{U}_i(\mathcal{J} \cup \{j\}, \mathbf{t}) \;\leq \Delta_i \mathcal{U}_i(\mathcal{J}' \cup \{j\}, \mathbf{t}) \qquad \forall\, i \in \mathcal{J} \cup \{j\} \;\&\; i \in \mathcal{J}' \cup \{j\} \\ \exists i \in \mathcal{J} \Delta_i \mathcal{U}_i(\mathcal{J}, \mathbf{t}) < 0 \quad \& \quad \exists i \in \mathcal{J}' \quad \Delta_i \mathcal{U}_i(\mathcal{J}', \mathbf{t}) < 0 \end{cases} \tag{21}$$

$$\text{for } \; \forall\, \mathcal{J} \subseteq \mathcal{J}' \subseteq \mathbb{I} \qquad \& \quad j \in \mathbb{I}$$

This sufficient condition states either one of these cases is verified: (1) in the first case of eq. (20), the marginal welfare $\Delta_j \mathcal{W}$ is monotone in $\mathcal{J}$: the welfare gain of adding country j grows with the size of the coalition $\mathcal{J}$. Moreover, the participation constraint of each member i is still respected when we include country j, and this monotonically in the coalition, from $\mathcal{J}$ to $\mathcal{J}'$, and the coalition is also stable without j. (2) In the second case of eq. (21), we do not require any condition of global welfare, but the participation constraint of each member i is respected when including country j, while it is violated when j is not present in $\mathcal{J}$ and $\mathcal{J}'$. Either one of these two conditions need to be respected for every pairs of sets $\mathcal{J} \subset \mathcal{J}'$ and every country j.

This condition, as well as its weaker counterpart in appendix (SCD-C-PC), are sufficient condition for SCD-C from below for $\widetilde{\mathcal{W}}$. It shows that the requirements for coalition building are much stronger as they need to verify if adding marginal members still satisfies the participation constraints of all the incumber members. In this context, the modified squeezing steps account for such constraint and thus:

Theorem The SCD-C-PC from below is *sufficient* for the application of modified squeezing algorithm, i.e. successive application of eq. (18), starting from $\{\varnothing, \mathbb{I}\}$ and eq. (19), to yield bounding sets $\underline{\mathcal{J}} \subseteq \mathbb{J} \subseteq \overline{\mathcal{J}}$ in CDCPs with participation constraints.

One of the advantage of our setting is that, for a small number of countries $\#\mathbb{I} \approx 10$, we can evaluate numerically if the sufficient conditions mentioned above are satisfied. The disadvantage of the model displayed above is that the large amount of heterogeneity, general equilibrium effects through energy markets and international trade, prevent the simple evaluation of those sufficient conditions analytically.

4 Quantification

The model is calibrated on a panel of ten regions to provide realistic predictions on the impact of optimal carbon policy. We first describe the data used. I then provide details on the quantification, which functional forms are used, and how the parameters are calibrated to match the data. I summarize in table 1 the dimensions of heterogeneity of the model.

4.1 Data

In this section, I describe briefly the data used to calibrate the model. We use data from the year 2018-2023, taken the average over that period to smooth out the effect of the COVID recession on energy and macroeconomic data.

In the present paper, we use a sample of 10 "regions": (i) US and Canada, (ii) China and Hong Kong, (iii) European Union, United Kingdom, other countries of the Schengen Area, (iv) South Asia (India, Pakistan, Bangladesh, Nepal) (v) Sub-saharian Africa, (vi) Middle-East and North Africa, (vii) Russia and CIS, (viii) Japan, Korea, Australia, Taiwan and Singapore, (ix) South-East Asia (Asean), (x) South and Central America. In a future iteration of this project, we will consider a panel of 25 countries and seven regions[14].

We use data for GDP per capita, in Purchasing Power Parity (PPP, in 2011 USD) from the World Bank, as collected and processed by the Maddison Project Bolt and van Zanden (2023). For the energy variables, we use the comprehensive data collected and processed in the Statistical Review of Energy Energy Institute (2024) that include data on production and consumption of various energy sources, including Oil, Gas and Coal. It also includes Proved reserves of those fossil fuels. For energy rent, we use the World Development Indicators that use national accounts to measure the share of GDP coming from the energy (oil, gas and coal) and natural resource rents.

Finally, for temperature, we use the same time series as Burke et al. (2015), which use the temperature at country level, averaged over the year and weighted by population across locations.

For trade variable, we take the trade flow and gravity variables compiled by the CEPII in Conte et al. (2022).

4.2 Welfare and Pareto weights

The welfare function that the climate agreement designer would maximize is the weighted sum of individual countries:

$$\mathcal{W} = \sum_{i \in \mathbb{I}} \mathcal{P}_i \, \omega_i \, \mathcal{U}_i$$

[14] In future extension, we will consider the following countries, which gather the G20 and additional large countries: United States, Canada, Germany, France, United Kingdom, Italy, Spain, China, India, Pakistan, Nigeria, South Africa, Saudi Arabia, Iran, Egypt, Turkey, Russia, Australia, Japan, South Korea, Indonesia, Thailand, Argentina, Brazil, Mexico, and seven regions: rest of European Union, rest of East Asia, rest of South Asia, rest of Sub-saharian Africa, rest of Middle-East, other CIS countries, others Latin American countries

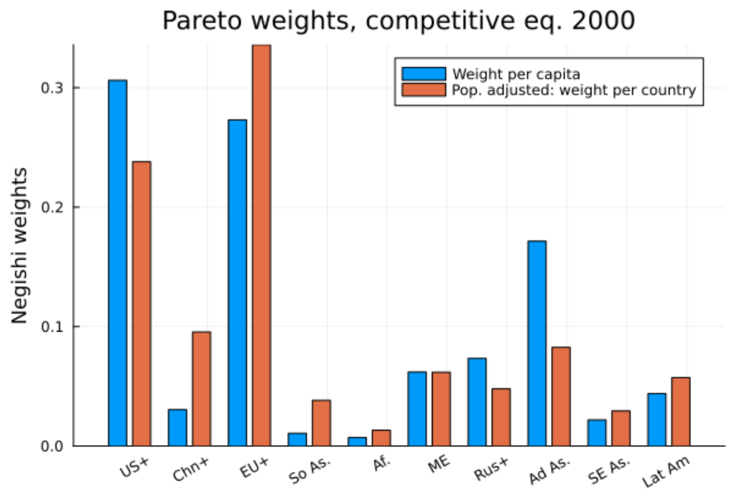
with $\mathcal{P}_i$ the population size per country, ω_i the Pareto weights and $\mathcal{U}_i$ the country indirect utility per capita. Note that the climate agreement designer maximizes the *world* welfare. If, in contrast, the designer only cares about maximizing the club welfare $\mathcal{W}(\mathbb{J}) = \sum_{i\in\mathbb{J}} \mathcal{P}_i\, \omega_i\, \mathcal{U}_i$, we would obtain unusual results. Indeed, the planner would gather a small club of rich and cold countries, that would not be affected by climate change and would subsidize carbon and fossil-fuel as well as imposing large tariffs on the Rest-of-World, to manipulate terms-of-trade. I give intuitions for such results in section 5.2, where countries unilaterally choose their climate and trade policy.

Following the discussion in Anthoff et al. (2009), Nordhaus (2011) and Nordhaus and Yang (1996), we would like to chose Pareto weights that eliminate redistributive effects that are orthogonal to climate change and climate policy. To that purpose, I choose the "Negishi" Pareto weights that make the preexisting competitive equilibrium efficient under that welfare metric. This implies:

$$\omega_i = \frac{1}{u'(\bar{c}_i)} \qquad \Leftrightarrow \qquad C.E.(\bar{c}_i) \in \underset{\bar{c}_i}{\operatorname{argmax}} \sum_i \mathcal{P}_i \omega_i u(\bar{c}_i)$$
$$\omega_i u'(\bar{c}_i) = \omega_j u'(\bar{c}_j) \qquad \forall i,j \ \in \mathbb{I}$$

where $\bar{c}_i$ is the consumption level in the present competitive equilibrium – the period 2019-2023 – absent future climate damage. This implies that the climate agreement and the climate policy does not look for redistributing across countries through goods and energy general equilibrium effects.

However, global warming, carbon taxation and tariffs do have redistributive effects, as it would change the distribution of c_i. These effects are taken into consideration in the choice of the policy as we will see in section 5.1.2. In the following picture we show the weights ω_i, and $\omega_i\widehat{\mathcal{P}}_i$ when adjusted for population $\widehat{\mathcal{P}}_i = \mathcal{P}_i/\mathcal{P}$.



In section 8.3, we compare the baseline result to the one with utilitarian weights $\omega_i = 1$, to see how the optimal climate agreement would change.

4.3 Macroeconomy, trade and production

For the macroeconomic part of framework, we consider standard utility and production functions. First, we consider Constant Relative Risk Aversion (CRRA) function, as well as climate damage in utility function. This implies that countries that have a very low production / GDP per capita still suffer potential large losses due to climate damages:

$$\mathcal{U}_i = \frac{(c_i \widetilde{\overline{\mathcal{D}}}^u(\mathcal{E}))^{1-\eta}}{1-\eta} = \frac{c_i^{1-\eta}}{1-\eta}\,\overline{\mathcal{D}}^u(\mathcal{E})$$

I calibrate the CRRA/IES parameter to be $\eta = 1.5$.[15] Moreover, the damage $\overline{\mathcal{D}}^u(\mathcal{E})$ is adjusted for the curvature in the utility function.

For production, I use a Nested CES framework. The firm combines a Cobb-Douglas bundle of capital k_i and labor ℓ_i[16] with a composite of energy e_i, with elasticity σ^y. Second, the energy e_i aggregate the different energy sources: oil and gas e^f, coal e^c_i and renewable/non-carbon e^r_i, with elasticity σ^e.

$$\text{Output} \qquad \bar{y}_i = \Big((1-\varepsilon)^{\frac{1}{\sigma^y}} (e_i)^{\frac{\sigma^y-1}{\sigma^y}} + \varepsilon^{\frac{1}{\sigma^y}} (k_i^\alpha \ell_i^{1-\alpha})^{\frac{\sigma^y-1}{\sigma^y}} \Big)^{\frac{\sigma^y}{\sigma^y-1}} \qquad\qquad y_i = \overline{\mathcal{D}}^y(\mathcal{E})\, z_i\, \bar{y}_i$$

$$\text{Energy} \qquad e_i = \Big((\omega^f)^{\frac{1}{\sigma^e}} (e^f_i)^{\frac{\sigma^e-1}{\sigma^e}} + (\omega^c)^{\frac{1}{\sigma^e}} (e^c_i)^{\frac{\sigma^e-1}{\sigma^e}} + (\omega^r)^{\frac{1}{\sigma^e}} (e^r_i)^{\frac{\sigma^e-1}{\sigma^e}} \Big)^{\frac{\sigma^e}{\sigma^e-1}}$$

To calibrate these functions, I set the capital-labor ratio to be $\alpha = 0.35$ following the literature. For energy share, I set $\varepsilon = 0.10$ to match the average energy cost share of $\frac{q^e_i e_i}{\mathrm{p}_i y_i} = 6\%$, as measured in Kotlikoff, Kubler, Polbin and Scheidegger (2021) and used in Krusell and Smith (2022). For the elasticity, I set $\sigma^y = 0.3$, following the estimation I did in Bourany (2022). This implies that capital/labor and energy are complement in production: a increase in the price of energy has a greater impact on output as it is less productive to "substitute away" to other inputs – capital, labor here, also decreasing in quantity due to complementarity. This aligns with other empirical and structural evidence on the impact of energy shocks, e.g. Hassler et al. (2019). For each energy sources, we calibrate the energy mix with oil-gas: $\omega^f = 0.56$, coal $\omega^c = 0.27$, and non-carbon $\omega^r = 0.17$, to match the aggregate shares in each of these energy sources. In the next section, I document how to match the individual countries energy mix using energy prices/costs. Finally, for the elasticity between energy inputs, I use the value $\sigma_e = 2$, following the rest of the literature, i.e. Kotlikoff, Kubler, Polbin and Scheidegger (2021) and **?**, and empirical estimates endogenous growth work on directed technical change.

[15]This is slightly lower than the standard value $\eta = 2$, for the reason that higher curvature would implies more inequal weights ω_i across different countries.

[16]Labor is inelastically supplied $\ell_i = \bar{\ell}_i$ for each country and normalized to 1 – since the country size $\mathcal{P}_i$ is already taken into account. As a result, all the variables can be seen as input per capita.

Finally, we use trade flow data to match the pattern of international trade in goods. First, I estimate a gravity regression between trade flow and geographical distance[17]– with fixed effects for importers and exporters – finding an elasticity with distance $\kappa = -1.72$. To rationalize that in the model, I project iceberg trade costs on this geographical distance $\tau_{ij} = d_{ij}^{\beta}$ and use the conventional trade elasticity $\theta = 5.63$, which implies $\beta = 0.375$. All the residuals difference in trade flows, not rationalized by trade costs, or differences in prices p_j or demand y_i are then explained by differences in preferences a_{ij}. We calibrate those parameters a_{ij} to minimize the distance – mean squared error – between model-generated trade shares $s_{ij} = \frac{c_{ij}\tau_{ij}\mathrm{p}_j}{c_i\mathbb{P}_i} = a_{ij}\frac{(\tau_{ij}\mathrm{p}_j)^{1-\theta}}{\sum_k a_{ik}(\tau_{ik}\mathrm{p}_k)^{1-\theta}}$, and observed shares $\bar{s}_{ij}$ in the data. Since our model imposes trade balance, which is not the case in the data due to current account imbalances, we cannot match exactly those trade shares, only approximately. It does match the fact that some countries are relying more on trade exports and imports – like China, East Asia and South-East Asia – compared to others – Middle East, Africa and Russia and CIS.

4.4 Energy markets

For the energy market, I match the energy mix of different countries, using the CES framework displayed above, as well as differences in cost of production. For the supply side, we use iso-elastic fossil extraction cost, to replicate the oil-gas supply of fossil producers.

First, let us recall that in out model, oil and gas are traded on international market, with demand e_i^f for demand from the final good firm, and supply e_i^x from fossil energy firm, extracting oil and gas from its own reserves. We use the extraction function $\mathcal{C}_i^f$ to have the following isoelastic form:

$$\mathcal{C}_i^f(e_i^x, \mathcal{R}_i)\mathbb{P}_i = \frac{\bar{\nu}_i}{1+\nu}\Big(\frac{e_i^x}{\mathcal{R}_i}\Big)^{1+\nu}\mathcal{R}_i\mathbb{P}_i$$

with inputs paid in the price of the consumption bundle, since the input $x_i^f = \mathcal{C}_i^f(e_i^x, \mathcal{R}_i)$ take the same CES form as the consumption demand c_i. This implies[18] the profit function :

$$\mathcal{P}_i\pi_i^f = q^f e_i^x - \mathcal{C}_i^f(e_i^x, \mathcal{R}_i) = \frac{\nu\bar{\nu}_i}{1+\nu}\big(\frac{e_i^x}{\mathcal{R}_i}\big)^{1+\nu}\mathcal{R}_i\mathbb{P}_i$$

We calibrate the three parameters $\mathcal{R}_i$, ν_i and $\bar{\nu}_i$ to match two important country levels variables: e_i^x and π_i^f as observes in the data. The reserve data $\mathcal{R}_i$ are taken directly from the data on oil and gas reserves documented by Energy Institute (2024). We calibrate the slope of this cost function $\bar{\nu}_i$ to match exactly the production of oil and gas e_i^x, as informed by that same data source. I then calibrate the curvature of the cost function to match the share $\eta_i^\pi = \frac{\pi_i^f}{y_i\mathrm{p}_i+\pi_i^f}$ of fossil energy

[17]The gravity regression is standard: $\log x_{ij} = \kappa \log d_{ij} + \alpha_i + \gamma_j$. In the model, $\tau_{ij} = d_{ij}^{\beta}$, we get $\kappa = (1-\theta)\beta$

[18]We express the oil-gas extraction with a cost function $x_i^f = \mathcal{C}_i^f$. We can also express analogously with the following production function:

$$e_i^x = g(x_i^f) = \big(\tfrac{1+\nu_i}{\bar{\nu}_i}\big)^{\frac{1}{1+\nu}}\mathcal{R}_i^{\frac{\nu_i}{1+\nu_i}}(x_i^f)^{\frac{1}{1+\nu_i}}$$

where the inputs x_i^f are paid in international goods, using the same CES demand for x_i^f as c_i.

profit as share of GDP. I calibrate ν to minimize the distance – mean squared error – between the model share η_i^π and the data, successfully matching the share within $5-10$ percentage points. Differences in oil and gas energy rent across countries are not only determined by differences in cost and technology, but also in differences in trade costs and market power – by the existence of OPEC which control more than 28% of oil supply and around 15% of natural gas supply. However, to keep the simplicity and tractability of the model, we refrain from adding an additional Armington structure over energy sources and oligopoly power over oil and gas. While discussed in Bornstein et al. (2023) and Hassler et al. (2010), I keep the analysis of such extensions for future research.

Second, I match the energy mix of the different countries by relying on the two assumptions made in the model: (i) coal and renewable are only traded at the country level: $\bar{e}_i^r = e_i^r$ and $\bar{e}_i^c = e_i^c$, and (ii) the cost function is linear in goods, i.e. the production is constant return to scale, implying $q_i^c = \mathcal{C}_i^c \mathbb{P}_i$ and $q_i^r = \mathcal{C}_i^r \mathbb{P}_i$. This allows to matching the energy mix of each country by calibrating the energy costs parameters $\mathcal{C}_i^c$ and $\mathcal{C}_i^r$ for each country to match the data $\frac{e_i^c}{e_i^f+e_i^c+e_i^r}$ and $\frac{e_i^r}{e_i^f+e_i^c+e_i^r}$. Using the CES framework above, we can match exactly the energy shares, successfully identifying countries that are more reliant on coal, vs. oil and gas vs. non-carbon/renewable: for example China and India are very coal dependent and Russia, Middle-East and United-States/Canada are the biggest consumer of oil and gas.

4.5 Climate system

We use the Nordhaus damage function.

4.6 Heterogeneity

Table 1: Heterogeneity across countries

Dimension of heterogeneity	Model parameter	Matched variable from the data	Source of the data
Population	Country size $\mathcal{P}_i$	Population	UN Population Prospect
TFP/technology/institutions	Firm productivity z_i	GDP per capita (2011-PPP)	World Bank/Maddison project
Productivity in energy	Energy-augmenting productivity z_i^e	Energy cost share	SRE Energy Institute (2024)
Cost of coal energy	Cost of coal production $\mathcal{C}_i^c$	Energy mix/coal share e_i^c/e_i	SRE Energy Institute (2024)
Cost of non-carbon energy	Cost of non-carbon production $\mathcal{C}_i^r$	Energy mix/coal share e_i^r/e_i	SRE Energy Institute (2024)
Local temperature	Initial temperature T_{it_0}	Pop-weighted yearly temperature	Burke et al. (2015)
Pattern scaling	Pattern scaling Δ_i	Sensitivity of T_{it} to world $\mathcal{T}_t$	Burke et al. (2015)
Oil-gas reserves	Reserves $\mathcal{R}_i$	Proved Oil-gas reserves	SRE Energy Institute (2024)
Cost of oil-gas extraction	Slope of extraction cost $\bar{\nu}_i$	Oil-gas extracted/produced e_i^x	SRE Energy Institute (2024)
Cost of oil-gas extraction	Curvature of extraction cost ν_i	Profit π_i^f / energy rent	World Bank / WDI
Trade costs	Distance iceberg costs τ_{ij}	Geographical distance $\tau_{ij} = d_{ij}^\beta$	CEPII Conte et al. (2022)
Armington preferences	CES preferences a_{ij}	Trade flows	CEPII Conte et al. (2022)

4.7 Calibration

Table 2: Baseline calibration ($\star$ = subject to future changes)

Technology & Energy markets			
α	0.35	Capital share in $F(\cdot)$	Capital/Output ratio
ϵ	0.12	Energy share in $F(\cdot)$	Energy cost share (8.5%)
σ^y	0.3	Elasticity capital-labor vs. energy	Complementarity in production (c.f. Bourany 2022)
ω^f	0.56	Fossil energy share in $e(\cdot)$	Oil-gas/Energy ratio
ω^c	0.27	Coal energy share in $e(\cdot)$	Coal/Energy ratio
ω^r	0.17	Non-carbon energy share in $e(\cdot)$	Non-carbon/Energy ratio
σ^e	2.0	Elasticity fossil-coal-non-carbon	Slight substitutability & Study by Stern
δ	0.06	Depreciation rate	Investment/Output ratio
$\bar{g}$	$0.01^\star$	Long run TFP growth	Conservative estimate for growth
Preferences & Time horizon			
ρ	0.03	HH Discount factor	Long term interest rate & usual calib. in IAMs
η	1.5	IES / Risk aversion	Standard calibration
n	0.0035	Long run population growth	Conservative estimate for growth
ω_i	1	Pareto weights	Uniforms / Utilitarian Social Planner
ω_i	$1/u'(c_i)$	Pareto weights	Negishi / Status-quo Social Planner
T	400	Time horizon	Time for climate system to stabilize
Climate parameters			
ξ^f	2.761	Emission factor – Oil & natural gas	Conversion 1 $MTOE \;\Rightarrow\; 1\; MT\; CO_2$
ξ^c	3.961	Emission factor – Oil & natural gas	Conversion 1 $MTOE \;\Rightarrow\; 1\; MT\; CO_2$
χ	$2.3/1e6$	Climate sensitivity	Pulse experiment: $100\,GtC \equiv 0.23°C$ medium-term warming
δ_s	0.0004	Carbon exit from atmosphere	Pulse experiment: $100\,GtC \equiv 0.15°C$ long-term warming
$\gamma^\oplus$	0.003406	Damage sensitivity	Nordhaus' DICE
$\gamma^\ominus$	$0.25\times\gamma^\oplus$	Damage sensitivity	Nordhaus' DICE & Rudik et al (2022)
α^T	0.5	Weight historical climate for optimal temp.	Marginal damage correlated with initial temp.
$T^\star$	14.5	Optimal yearly temperature	Average spring temperature / Developed economies

5 Optimal policy benchmarks without participation constraints

We provide three benchmarks/special cases for optimal policy when participation is exogenous. First, we consider a global social planner policy that maximizes aggregate welfare, representing the cooperative allocation. Second, in the non-cooperative Nash-equilibrium, each country implements its unilaterally optimal policy.

5.1 Global Climate Policy with cooperation

The cooperative policy depends on the availability of redistribution instruments. With unlimited instruments, in particular lump-sum transfers, the optimal tax is the social cost of carbon, a measure of the marginal cost of climate change. Without transfers, the optimal tax needs to account for inequality across countries and trade leakage effects. Accounting for inequality and lack of redistribution, the optimal tax can be lower.

5.1.1 First Best allocation with unlimited instruments

With unlimited instruments, the social planner uses lump-sum transfers to redistribute across countries and offset the negative effects of climate change and carbon taxation. In this context, the optimal tax is the standard Pigouvian tax, which is the social cost of carbon.

5.1.2 Second-Best Ramsey problem without transfers

When the social planner does not have access to transfers, the carbon tax needs to account for redistributive effects. The optimal tax needs to be corrected for (i) the heterogeneous effects of climate change, (ii) the redistributive effects on energy markets, (iii) the distortion of demand, (iv) the leakage effects of trade.

5.2 Unilateral policies: Nash-equilibrium

If countries act non-cooperatively, the optimal energy policy does not account for the externality imposed on other countries. Moreover, each country might use trade tariffs strategically for terms-of-trade manipulation.

5.2.1 Energy policy

Each country, when setting the carbon tax, accounts solely for the cost of climate change on its own country, a typical example of the free-riding problem.

5.2.2 Trade-policy

The unilateral trade policy is used strategically to manipulate terms-of-trade, leading to a race-to-the-bottom trade war.

6 Optimal Climate agreement

The main result of the optimal design of climate agreements is that the choice depends on the balance between two effects: the distortionary effect of the carbon tax, and the cost of tariffs of other trade partners, related to gains from trade. We note that for several countries like fossil-fuel producers or developing economies, the first outweighs the second, implying that they would not participate in a climate agreement unless the tax is decreased. The optimal agreement may not include the entire world and potentially set a carbon tax lower than the Pigouvian level – the Social Cost of Carbon.

6.1 Trade-offs: gains from trade vs. distortionary effects of carbon taxation

The following two effects influence the design of the agreement. First, the distortionary effect of the carbon tax differs across countries, and some countries – poor, closed to trade or cold countries and fossil-fuel producers have very large gains from free-riding. Second, the cost of tariffs of other trade partners, related to gains from trade, also differs across countries.

6.2 Welfare decomposition

To understand the mechanisms through which climate change, carbon taxation and tariffs affect welfare, I provide a first-order approximation of welfare to shed light on different mechanisms.

6.3 Optimal climate agreement

The optimal agreement may not include the entire world and potentially set a carbon tax lower than the social cost of carbon.

7 Extensions: Additional instruments - Impact of additional policy instruments

7.1 Fossil-fuels specific tariffs

7.2 Transfers and Loss and damage funds

8 Robustness

The optimal agreement can change depending on the impact of climate change or the impact of tariffs.

8.1 Climate sensitivity

8.2 Gains-from-trade

8.3 Inequality and redistributive effects

9 Conclusion

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