Trade, Transport, and Emissions: Quantifying a Green Economy

PRELIMINARY AND INCOMPLETE

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Abstract

This paper analyzes the role of international trade in mitigating climate change. We characterize the production, consumption, and trade patterns in a perfectly green economy where emissions are priced in. In our general equilibrium model of international trade, production and transportation of goods generate CO_2 emissions and aggravate climate change. Our framework is designed to match cross-country and cross-sector data for trade, production and emissions stemming from fossil fuels and different modes of transportation. Our preliminary findings suggest that the environmentally optimal allocation of production could decrease emissions by 20% and double welfare. This comes at the expense of real income which is decreasing in all regions.

1 Introduction

Climate change is considered one of the biggest challenges of our society. A first order priority in the fight against global warming is to drastically reduce greenhouse gas emissions. These emissions occur both during the production and the transport of a product. Many countries take these considerations into account when deciding about new polices. For example, US President Joe Biden's infrastructure bill includes roughly USD 2 trillion for both improving the transportation infrastructure and investing in greener energy (Zarracina et al.; 2021).

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This paper takes a more global view and asks the research question: "What would production, consumption, and trade look like if emissions were priced in?" While more trade leads to more transport and thus higher transport emissions, the effect of trade on production emissions is ambiguous. Depending on whether a country sources from origins with cleaner or dirtier production technologies, the overall effect on climate change might be positive or negative. Therefore, it is unclear whether more trade would aggravate or mitigate climate change. We aim at characterizing the production, consumption, and trade patterns in a perfectly green economy where emissions are priced in. Ultimately, our goal is to unveil the potential of changes in domestic and international trade flows in mitigating climate change.

We build a general equilibrium model of international trade in which production and transportation of goods generate CO_2 emissions and aggravate climate change. Emissions of greenhouse gases are a pure cross-border externality, which governments can tax using an environmental policy options, a tax applied over the price of inputs. The structure of the world economy builds on a multi-industry, multi-country Armington (1996) model with environmental externalities, as in Shapiro (2016). We extend this basic framework to take into account heterogeneity in emissions by transportation mode, which are among the main drivers of climate change. Our framework is designed to match cross-country and cross-sector data for trade, production and emissions stemming from fossil fuels and different modes of transportation.

We combine our model with input output data from the WIOD (2015a) to compute trade and production in a perfectly green economy with cooperative carbon taxes. Our preliminary findings show that a moderate decrease in emissions of around 20% can lead to a substantial increase in welfare. This comes at the expense of real income which is decreasing in all regions. These effects of the cooperative carbon taxes serve as a benchmark to discuss other policies in a future version of this paper.

This paper contributes to several strands of the literature. Previous models on trade and transportation feature a per-unit transportation fee and solves the problem of transportation firms separately (Hummels et al.; 2009; Wong; 2020). In our analysis, freight rates are determined by solving the maximization problem of the firm together with the price of other inputs. Another set of papers models the transport sector with a bottom-up approach based on the distance and the weight-to-value ratios (Shapiro; 2016; Cristea et al.; 2013). These studies provide detailed comparisons of production vs. transport emissions and analyze the role of international trade in emissions from a welfare perspective. Building on their work, we characterize the perfectly green economy and analyze the optimal policy scenario.

For analyzing optimal carbon taxes in an open economy, we take the quantitative framework of Ossa (2014) as a starting point and incorporate carbon emissions as an externality. Several authors have studied unilateral trade policy in the presence of externalities (Markusen; 1975; Copeland; 1996; Kortum and Weisbach; 2020). Perhaps most related in spirit is Farrokhi and Lashkaripour (2021) who analyze the role of trade policy in reducing global carbon emissions. They also build a multi-country multi-industry general equilibrium trade model and focus on firm's delocation response to policy. Our model differs in several ways. First, we allow for different sources of energy which is an important driver in production emissions. Second, we model emissions from the transportation sector explicitly, so that policy can affect the transportation sector directly. Third, we characterize the production and trade patterns that arise in a perfectly green economy.

This paper is organized as follows. Section 2 introduces the model and section 3 characterizes the equilibrium and discusses optimization. Section 4 describes the data, while section 5 presents and discusses the results. Section 6 concludes.

2 Theory

We build a general equilibrium model of international trade in manufactures in which production and transportation of goods generate CO_2 emissions and aggravate climate change. Emissions of greenhouse gases are a pure cross-border externality which governments can tax using one environmental policy option, a tax on fossil fuel extraction. Our model allows us to study how trade and production patterns would look like in a "green economy" with emissions efficiently priced. Ultimately, we aim at unveiling the potential of changes in domestic and international trade flows as a tool to mitigate climate change.

The structure of the world economy builds on a multi-industry, multi-country Armington (1996) model with environmental externalities, as in Shapiro (2016). We extend this basic framework by including in the production technology transportation services, which are considered one of the the main drivers of climate change. We also include sectorial input-output linkages, as in Caliendo and Parro (2014). This makes sure that carbon taxes impacts the production structure in all sectors according to how much production relies on fossil fuels. Our framework is designed to match cross-country and cross-sector data for trade, production and emissions stemming from fossil fuels and different modes of transportation.

In what follows, subscripts denote countries. An ij subscript represents a flow from country i to country j. Superscripts denote sectors.

2.1 Preferences

We model the economy using a multi-sector Armington (1969) structure, in which each sector in each country produces a specific variety. Consumer preferences are described by a Cobb-Douglas-CES utility function that also features damage from carbon emissions, as in Shapiro (2021):

$$C_j = \left[\prod_s (C_j^s)^{\mu_j^s} \right] \left[\frac{1}{1 + \delta(Z - Z_0)} \right] \tag{1}$$

$$C_j^s = \prod_m \left[\left(\sum_i (C_{ij}^{sm})^{\frac{\sigma_s - 1}{\sigma_s}} \right)^{\frac{\sigma_s}{\sigma_s - 1}} \right]^{\mu_j^{T,sm}}$$

where C_{ij}^{sm} is the consumption of the sector s variety coming from country i in country j via transportation mode m. The lower CES nest aggregates sector-specific varieties imported from multiple countries through a specific mode of transportation m. The elasticity of substitution σ_s is sector specific, but invariant across countries. The lower Cobb-Douglas nest aggregates varieties across different modes of transportation. We have that

$$\mu_j^{T,sm} = \sum_i X_{ij}^{sm} / \sum_m \sum_i X_{ij}^{sm}$$

and

$$\mu_j^s = \sum_i \sum_m X_{ij}^{sm} / \sum_s \sum_m \sum_i X_{ij}^{sm}$$

those are just expenditure shares. The upper Cobb-Douglas nest aggregates varieties across different sectors. $\mu_j^{S,s}$ is the share of national expenditure that accrues to sector s goods.

δ is the parameter that captures climate change damages. Z_0 represents a reference or baseline level of global CO2 emissions used to calibrate the damage parameter, and Z represents the global emissions in a particular scenario. (From Shapiro 2021) CO2 emissions are a pure externality that the representative agent takes as given when making consumption decisions. This model has no feedback loop from the environment to trade - the negative environmental externality of trade decreases utility, but carbon emissions do not affect trade *directly*.

2.2 Supply

In each sector, firms are responsible for the production *and* delivery of goods. Production employs labor, clean intermediates, fossil fuels used in production and transportation services. Transportation services allow firms to serve international markets through different modes of transportation and implicitly also requires the use of fossil fuels that create environmental externalities. The technology is given by:

$$y_{ij}^{sm} = \phi_i^s \left[\left(\frac{l_i^s}{\beta_i^{L,s}} \right)^{\beta_i^{L,s}} \prod_k \left(\frac{I_i^{k,s}}{\beta_i^{I,ks}} \right)^{\beta_i^{I,ks}} \right]^{(1-\beta_{ij}^{T,sm})} \left(\frac{T_{ij}^{sm}}{\beta_{ij}^{T,sm}} \right)^{\beta_{ij}^{T,sm}} \tag{2}$$

Where y_{ij}^{sm} is an origin-destination-sector-mode-of-transportation specific variety; ϕ_i^s is a sector-specific productivity; l_i^s is labor; and T_{ij}^{sm} are transportation services. I_i^{sk} is the consumption of sector k intermediates in sector s, which is described in a nested-CES fashion, just as (1). $\beta_i^{L,sk}$ and $\beta_i^{I,s}$ are the share of labor, and intermediates in gross production net of transportation services. $\beta_{ij}^{T,sm}$ is the share of transportation services to country j via mode m in gross production. Observe that $(\beta_i^{L,s} + \sum_k \beta_i^{I,ks})(1 - \beta_{ij}^{T,sm}) + \beta_{ij}^{T,sm} = 1$.

We define θ_{ij}^s as an additional iceberg-style trade cost that capture bilateral trade frictions beyond transportation costs, which are standard in the gravity literature (common language, border effects etc.).

2.3 Environment

CO_2 emissions Z_i are given by :

$$Z_i = \sum_s \sum_m \sum_j \chi_i^s \frac{X_{ij}^{sm}}{\omega_{ij}^{sm}} \tag{3}$$

where χ_i^s represent the CO_2 emissions per unit of production units. In reality, χ_i^s is only different from zero for fossil fuel extraction sector

2.4 Environmental/carbon taxes on dirty inputs

Our quantitative exercise aims at computing a counterfactual economy in which the environmental externality is efficiently priced. In our setting, polution is associated with the employment of fossil fuels in production and in transportation. As mentioned by Dixit (1985), "the Bhagwati-Johnson principle of targeting (...) states that a distortion is best countered (...) by a tax instrument that acts directly on the relevant margin". Hence, we define production carbon taxes ($\tau_i^{F,s}$) that allow governments to directly pick the socially efficient price of production fossil fuels. Environmental taxes are also rebated lump sum to consumers.

3 Equilibrium and Welfare

3.1 Equilibrium in Levels

The assumptions on goods consumption make sure there is trade between countries and sectors at all prices as varieties are purchased from all sources. Firms face standard CES demands:

$$c_{ij}^{sm} = \frac{[p_{ij}^{sm} \theta_{ij} \tau_i^{F,s}]^{-\sigma_s}}{(P_j^{sm})^{1-\sigma_s}} E_j \mu_j^{T,m} \mu_j^{S,s}, \tag{4}$$

where p_{ij}^{sm} is the price of a variety s produced at country i and shipped to country j using transportation mode m. E_j is total expenditure of country j consumers. P_j^{sm} is the CES consumption price index for sector s goods at j shipped through mode m, which is given by:

$$P_j^{sm} = \left(\sum_i (p_{ij}^{sm} \theta_{ij}^s \tau_i^{F,s})^{1-\sigma_s} \right)^{\frac{1}{1-\sigma_s}}. \tag{5}$$

It aggregates in the following ways:

$$P_j^s = \prod_m \left(\frac{P_j^{sm}}{\mu_j^{T,sm}} \right)^{\mu_j^{T,sm}} \tag{6}$$

P_j^s is the price of the sector s intermediate input.

$$P_j = \prod_s \left(\frac{P_j^s}{\mu_j^s} \right)^{\mu_j^s} \tag{7}$$

P_j is the standard CES-price index.

Perfect competition implies that the price equals marginal costs. Hence, p_{ij}^{sm} depends on the productivity ϕ_i^s and on the price of the input bundle ω_{ij}^{sm}:

$$p_{ij}^{sm} = \frac{\omega_{ij}^{sm}}{\phi_i^s} \tag{8}$$

The price of the input bundle aggregates the price of labor (w_i), intermediates and transportation ($r_{ij}^{T,sm}$) in a Cobb-Douglas fashion:

$$\omega_{ij}^{sm} = [(w_i)^{\beta_i^{L,s}} \prod_k (P_i^k)^{\beta_i^{I,ks}}]^{(1-\beta_{ij}^{T,sm})} [r_{ij}^{T,sm}]^{\beta_i^{T,sm}}$$

Substituting equation (7) into the price-index yields:

$$P_j^{sm} = \left(\sum_i (\frac{\omega_{ij}^{sm}}{\phi_i^s} \theta_{ij}^s)^{1-\sigma_s} \right)^{\frac{1}{1-\sigma_s}}. \quad (9)$$

Defining $X_{ij}^{sm} = p_{ij}^{sm} \theta_{ij}^s c_{ij}^{sm}$ as the value of trade flows of goods from sector s in country i to country j through transportation mode m and using equations (x) and (xx), we have:

$$X_{ij}^{sm} = \left(\frac{\omega_{ij}^{sm}}{\phi_i^s} \theta_{ij}^s \right)^{1-\sigma_s} (\tau_i^{F,s})^{-\sigma_s} (P_j^{sm})^{\sigma_s - 1} E_j \mu_j^{T,m} \mu_j^{S,s}. \quad (10)$$

This is a sector-level gravity equation decomposing bilateral trade flows into bilateral trade costs and importer and exporter specific factors.

Next, we define the market clearing. Labor is mobile across sector, but not across countries. We also fix the stock of transportation services necessary to ship goods from a country i to another j via mode m.

The wage bill is given by:

$$w_i L_i = \sum_s \sum_j \sum_m \beta_i^{L,s} (1 - \beta_{ij}^{T,sm}) X_{ij}^{sm} \quad (11)$$

where $L_i = \sum_s l_i^s$.

Rents generated by the provision of mode m transportation services are given by:

$$r_{ij}^{T,sm} T_{ij}^{sm} = \beta_{ij}^{T,sm} X_{ij}^{sm} \quad (12)$$

for all m, i, s and j.

Expenditure with final goods equals income gains of labor and rents from provision of transportation services

$$E_i^F = w_i L_i + \sum_m \sum_j \sum_s r_{ij}^{T,sm} T_{ij}^{sm} \tag{13}$$

Expenditure with intermediates is given by:

$$E_i^I = \sum_s \sum_m \sum_j \sum_k \beta_i^{I,ks} (1 - \beta_{ij}^{T,sm}) X_{ij}^{sm} \tag{14}$$

Market clearing implies that total expenditure equals:

$$E_i = E_i^F + E_i^I \tag{15}$$

We can now define an equilibrium of this economy.

Definition 1 For given carbon taxes, an equilibrium can be defined as a set of $E_i, E_i^F, E_i^I w_i, r_{ij}^{T,sm}$ such that:

$$E_i = E_i^F + E_i^I \tag{16}$$

$$E_i^F = w_i L_i + \sum_m \sum_j \sum_s r_{ij}^{T,sm} T_{ij}^{sm} \tag{17}$$

$$E_i^I = \sum_s \sum_m \sum_j \sum_k \beta_i^{I,ks} (1 - \beta_{ij}^{T,sm}) X_{ij}^{sm} \tag{18}$$

$$w_i L_i = \sum_s \sum_j \sum_m \beta_i^{L,s} (1 - \beta_{ij}^{T,sm}) X_{ij}^{sm} \tag{19}$$

$$r_{ij}^{T,sm} T_{ij}^{m} = \beta_{ij}^{T,sm} X_{ij}^{sm}$$

where

$$X_{ij}^{sm} = \left(\frac{\omega_{ij}^{sm}}{\phi_i^s}\theta_{ij}^s\right)^{1-\sigma_s} (P_j^{sm})^{\sigma_s-1} E_j \mu_j^{T,m} \mu_j^{S,s}$$

$$\omega_{ij}^{sm} = [(w_i)^{\beta_i^{L,s}} \prod_k (P_i^k)^{\beta_i^{I,ks}}]^{(1-\beta_{ij}^{T,sm})} [r_{ij}^{T,sm}]^{\beta_i^{T,sm}}$$

$$P_j^{sm} = \left(\sum_i (\frac{\omega_{ij}^{sm}}{\phi_i^s}\theta_{ij}^s)^{1-\sigma_s}\right)^{\frac{1}{1-\sigma_s}}$$

with

$$P_j^s = \prod_m \left(\frac{P_j^{sm}}{\mu_j^{T,sm}}\right)^{\mu_j^{T,sm}}$$

3.2 Equilibrium in Changes

In order to take the model to the data, we use the "exact hat algebra" method popularized by Dekle et al. (2007). This involves rewriting the equilibrium expressed in Definition 1 in terms of changes in tariffs and all endogenous variables. Performing counterfactual exercises with equilibrium in changes makes it unnecessary to recover some structural parameters difficult to identify in the data, like $\{l_i^s$ and ϕ_i^s. As pointed out by Ossa (2016), it also ensures that counterfactual effects of changes in tariffs can be computed from a reference point that perfectly matches trade flows and tariffs. In what follows, a counterfactual version of a variable x is denoted by x'. The proportional change is then given by $\hat{x} = x'/x$.

Definition 2 For given counterfactual carbon taxes, an equilibrium is a set of $\{\hat{E}_i, \hat{E}_i^F, \hat{E}_i^I, \hat{w}_i, \hat{r}_{ij}^{T,sm}\}$ such that:

$$\hat{E}_i = \frac{E_i^F}{E_i}\hat{E}_i^F + \frac{E_i^I}{E_i}\hat{E}_i^I$$

$$\hat{E}_i^F = \frac{w_i L_i}{E_i^F}\hat{w}_i + \sum_j \sum_m \sum_s \frac{r_{ij}^{T,sm} T_{ij}^{sm}}{E_i^F}\hat{r}_{ij}^{T,sm}$$

$$E_i^I = \sum_s \sum_m \sum_j \sum_k (\beta_i^{I,ks}(1-\beta_{ij}^{T,sm}) X_{ij}^{sm}/E_i^I)\hat{X}_{ij}^{sm} \tag{20}$$

$$\hat{w}_i = \sum_m \sum_s \sum_j (\beta_i^{L,s}(1-\beta_{ij}^{T,sm})X_{ij}^{sm}/w_i L_i)\hat{X}_{ij}^{sm}$$

$$\hat{r}_{ij}^{T,sm} = \hat{X}_{ij}^{sm}$$

$$\hat{P}_j^{sm} = \left(\sum_i \frac{X_{ij}^{sm}}{(\sum_{r=1}^{N} X_{rj}^{sm})} [(\hat{\omega}_{ij}^{sm}]^{1-\sigma_s} \right)^{\frac{1}{1-\sigma s}}$$

$$\hat{X}_{ij}^{sm} = (\hat{\omega}_i^s)^{1-\sigma^s} (\hat{P}_j^{sm})^{\sigma^s - 1} \hat{E}_j$$

$$\hat{\omega}_{ij}^{sm} = \left[\left((\hat{w}_i)^{\beta_i^{L,s}} \prod_k (\hat{P}_i^k)^{\beta_i^{I,ks}} \right]^{(1-\beta_{ij}^{T,sm})} \left[\hat{r}_{ij}^{T,sm} \right]^{\beta_{ij}^{T,sm}}$$

3.3 Changes in Emissions

Changes in emissions are given by:

$$\hat{Z}_i = \frac{\sum_j \sum_s \sum_m \chi_i^{F,s} (\hat{X}_{ij}^{sm} X_{ij}^{sm} / \hat{\omega}_{ij}^{sm} \omega_{ij}^{sm})}{Z_i} \tag{21}$$

$$\hat{Z}_i = \frac{\sum_j \sum_s \sum_m (\hat{X}_{ij}^{sm} / \hat{\omega}_{ij}^{sm}) Z_{ij}^{sm}}{Z_i} \tag{22}$$

3.4 Welfare

Welfare in country i can be described by the indirect utility function:

$$W_i = \frac{E_i}{P_i} \left[\frac{1}{1 + (\mu_d^{-1} \sum_j Z_j)^2} \right] \tag{23}$$

We define global welfare as: $W = \prod_i W_i$. Hence, global welfare changes equal:

$$\hat{W} = \prod_i \hat{W}_i \tag{24}$$

In the algorithm described below, we optimize $\hat{W}$, which is equivalent to optimizing W.

3.5 Optimization

To compute carbon taxes and endogenous variables in a green economy, we follow the MPEC approach, solving the following problem:

$$\min_{\{\tau_i^{F,s}, \hat{E}_i, \hat{E}_i^F, \hat{E}_i^I, \hat{w}_i, \hat{r}_{ij}^{T,sm}\}} \hat{W}$$

treating the equilibrium conditions in changes as constraints.

4 Data

To calibrate the model, we need the following variables:

- X_{ij}^{sm} mode specific trade and production flows
- $\beta_{ij}^{T,sm}$ share of transportation costs on gross production by mode and destination
- $\beta_i^{L,s}$, $\beta_i^{I,ks}$ share of labor and clean intermediates on production net of transportation costs
- σ_s elasticity of substitution
- $\chi_i^{F,s}$ emissions of fossil fuels

We use several data sources. The World Input Output Database (WIOD) (2015b) provides data on trade and production flows by country and sector. To obtain X_{ij}^s, we sum the input output table across column sectors. We combine this data set with mode shares from the international merchandise trade data set from UNCTADstat to create the matrix X_{ij}^{sm}. The share of transportation costs on gross production by mode and destination $\beta_{ij}^{T,sm}$ is created using the intermediate trade and production flows from the WIOD data, where T represents the transport related columns sectors. Thereby, the industries postal and courier activities are added to the water transport sector. The share of clean intermediates on production net of transportation costs $\beta_i^{I,ks}$ is calculated as the share of trade and production flows divided by output net of transportation costs. The transportation costs are calculated with transport cost share data from UNCTADstat that is applied to the WIOD. The share of labor on production net of transportation costs $\beta_i^{L,s}$ is the residual. The emissions of fossil fuels $\chi_i^{F,s}$ stem from the WIOD environmental accounts (2015b). We use the elasticity of substitution σ_s as in Felbermayr et al. (2022) displayed in table 6 in the appendix. We aggregate countries into four regions of the world (US, EU, China, and the Rest of the World) and group the services sectors "C33-U" together.

Table 1 shows the summary statistics for the data by sector. Figure 1 shows the trade values by mode of transportation and figure 2 shows trade and production across countries.

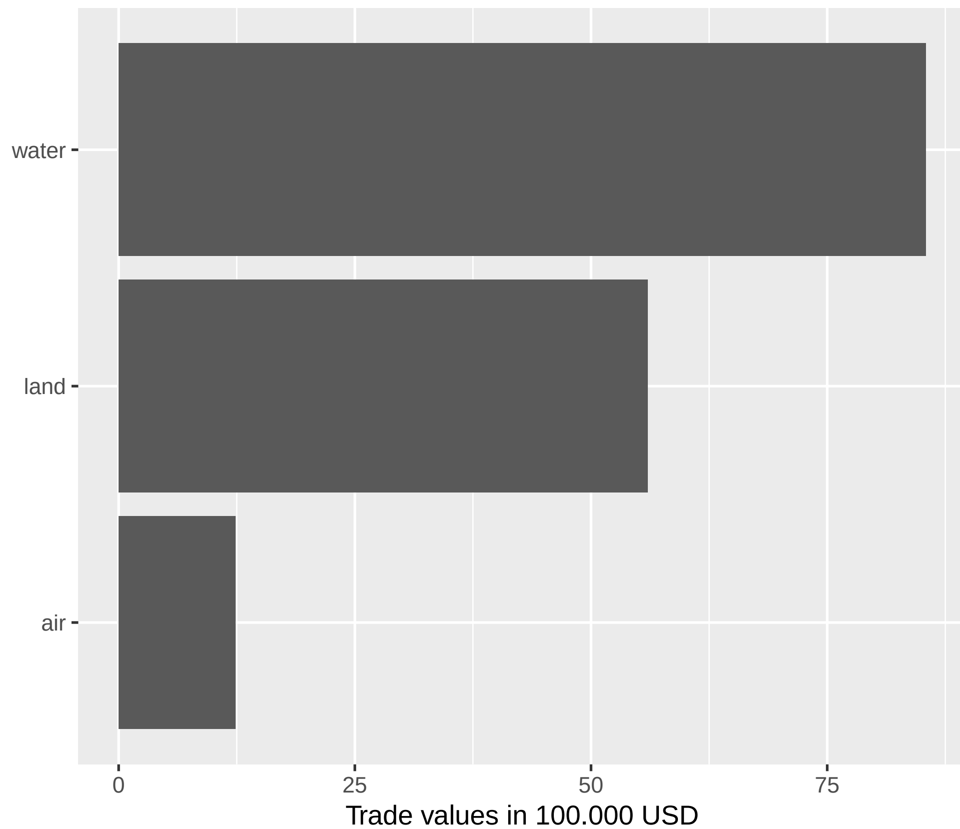
	Sector	Trade/GDP %	Emissions %
1	Crop and animal production	41.95	3.40
2	Forestry and logging	43.48	0.72
3	Fishing and aquaculture	37.09	0.17
4	Mining and quarrying	43.46	6.49
5	Manufacture of food and tobacco	74.46	2.91
6	Manufacture of textiles	75.29	1.07
7	Manufacture of wood	72.27	0.43
8	Manufacture of paper	72.99	1.28
9	Printing and media	61.13	0.10
10	Manufacture of coke and refined petroleum	81.88	5.59
11	Manufacture of chemicals	75.67	14.01
12	Manufacture of basic pharmaceuticals	61.97	0.04
13	Manufacture of rubber and plastic	73.02	3.48
14	Manufacture of other non-metallic minerals	69.85	31.66
15	Manufacture of basic metals	80.99	24.45
16	Manufacture of fabricated metals	68.63	0.59
17	Manufacture of computers	71.02	0.28
18	Manufacture of electrical equipment	76.75	0.46
19	Manufacture of machinery n.e.c.	69.80	0.99
20	Manufacture of motor vehicles	76.52	0.39
21	Manufacture of other transport equipment	70.66	0.33
22	Manufacture of furniture	61.52	1.17

Note:

This table shows the summary statistics of gross output divided by GDP and emissions as a percent of total emissions.

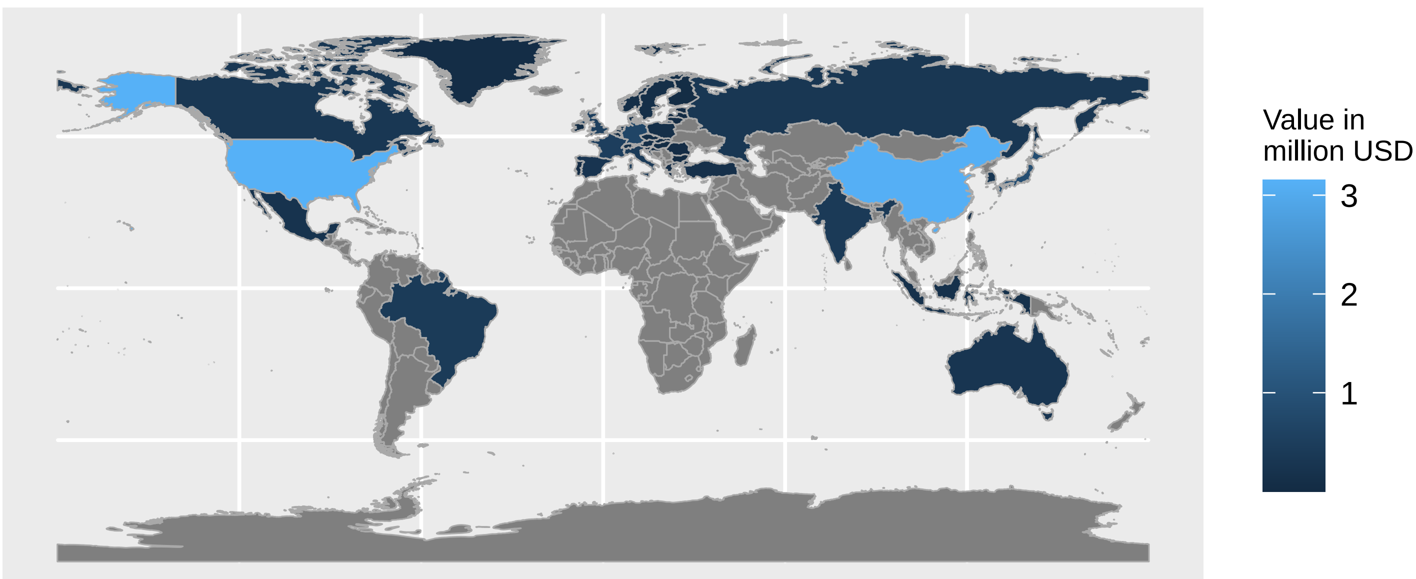
Table 1: Summary Statistics

Fig. 1: Trade values by mode of transportation



This graph shows the overall trade values by three modes of transportation in 100.000 USD.

Fig. 2: Trade values across countries



This map shows the trade and production across countries.

5 Results

This section presents the results from bringing the model to the data. To characterize the perfectly green economy, we calculate the socially optimal carbon taxes. Table 2 shows our main results. On average, emissions decrease in all four world regions while welfare increases. A moderate decrease in emissions of around 20% can lead to welfare almost doubling. The trade pattern also changes: The US and the rest of the world would import less in the perfectly green economy, while China and the EU would import more. However, these large increases in welfare come at the expense of real income which decreases.

Table 2: Average Changes (%) in Imports, Emissions, and Welfare

	Avg. Imports			Emissions	Welfare	Real Income	Wages
	AIR	LAND	WATER				
China	24	18	19	-15	97	-17.52	5.38
European Union	14	13	13	-20	89	-20.66	1.22
Rest of the World	-8	-7	-8	-28	72	-27.99	-5.13
USA	-11	-15	-16	-8	97	-17.68	4.08

Note:

This table shows the average changes in imports, emissions, and welfare by the three modes of transport for the four regions in the model, all compared to the status quo.

The next set of tables 3, 4, 5 show the changes in imports by sector for each transport mode and region compared to the status quo. For each sector, the trade pattern changes across countries in order to create the perfectly green economy. The sectoral changes in trade patterns are moderate compared to the welfare changes seen in table 2.

Table 3: Changes in Imports (%). Mode: Water

#	Sector	China	EU	ROW	USA
1	Crop and animal production	10	18	-18	11
2	Forestry and logging	1	60	-24	-11
3	Fishing and aquaculture	-4	13	1	-4
4	Mining and quarrying	15	-1	14	-20
5	Manufacture of food and tobacco	17	20	-10	-14
6	Manufacture of textiles	2	9	0	-1
7	Manufacture of wood	37	-1	-1	-42
8	Manufacture of paper	-21	26	8	-17
9	Printing and media	121	-23	1	-12
10	Manufacture of coke and refined petroleum	34	20	-2	-24
11	Manufacture of chemicals	15	11	-4	-13
12	Manufacture of basic pharmaceuticals	69	44	-19	-38
13	Manufacture of rubber and plastic	19	15	-13	-4
14	Manufacture of other non-metallic minerals	34	38	22	-72
15	Manufacture of basic metals	21	6	-8	-7
16	Manufacture of fabricated metals	22	19	-13	-8
17	Manufacture of computers	20	14	-10	-19
18	Manufacture of electrical equipment	18	14	-9	-28
19	Manufacture of machinery n.e.c.	30	18	-11	-22
20	Manufacture of motor vehicles	25	24	-11	-22
21	Manufacture of other transport equipment	34	9	-5	-15
22	Manufacture of furniture	37	18	-22	-21
23	Services	16	14	-8	-11

Note:

This table shows the changes in imports by sector for the share that was transported by water.

Table 4: Changes in Imports (%). Mode: Land

	Sector	China	EU	ROW	USA
1	Crop and animal production	12	20	-17	10
2	Forestry and logging	-6	60	-7	-10
3	Fishing and aquaculture	-16	13	-5	-5
4	Mining and quarrying	15	-4	13	-16
5	Manufacture of food and tobacco	13	19	-11	-11
6	Manufacture of textiles	2	10	-1	-2
7	Manufacture of wood	31	-5	7	-36
8	Manufacture of paper	-24	18	3	-23
9	Printing and media	37	-28	6	-16
10	Manufacture of coke and refined petroleum	15	16	1	-25
11	Manufacture of chemicals	14	9	-5	-15
12	Manufacture of basic pharmaceuticals	15	37	-17	-29
13	Manufacture of rubber and plastic	16	16	-13	-2
14	Manufacture of other non-metallic minerals	17	-1	32	-72
15	Manufacture of basic metals	21	5	-8	-8
16	Manufacture of fabricated metals	15	19	-14	-5
17	Manufacture of computers	24	13	-11	-18
18	Manufacture of electrical equipment	21	11	-11	-28
19	Manufacture of machinery n.e.c.	20	18	-11	-18
20	Manufacture of motor vehicles	14	22	-7	-19
21	Manufacture of other transport equipment	31	2	-4	-16
22	Manufacture of furniture	32	22	-19	-11
23	Services	15	12	-8	-11

Note:

This table shows the changes in imports by sector for the share that was transported by land.

Table 5: Changes in Imports (%). Mode: Air

	Sector	China	EU	ROW	USA
1	Crop and animal production	9	15	-18	7
2	Forestry and logging	-4	59	-28	-12
3	Fishing and aquaculture	-8	12	3	-4
4	Mining and quarrying	15	2	15	-21
5	Manufacture of food and tobacco	16	20	-11	-13
6	Manufacture of textiles	2	11	-2	-4
7	Manufacture of wood	39	-2	-3	-40
8	Manufacture of paper	-23	31	7	-16
9	Printing and media	132	-17	-4	-10
10	Manufacture of coke and refined petroleum	23	16	-4	-24
11	Manufacture of chemicals	16	12	-5	-11
12	Manufacture of basic pharmaceuticals	69	20	-13	-20
13	Manufacture of rubber and plastic	19	14	-12	-5
14	Manufacture of other non-metallic minerals	50	64	19	-62
15	Manufacture of basic metals	21	8	-8	-6
16	Manufacture of fabricated metals	21	17	-13	-8
17	Manufacture of computers	26	12	-9	-9
18	Manufacture of electrical equipment	23	15	-9	-11
19	Manufacture of machinery n.e.c.	29	16	-11	-12
20	Manufacture of motor vehicles	24	21	-12	-17
21	Manufacture of other transport equipment	35	11	-5	-9
22	Manufacture of furniture	46	14	-19	-13
23	Services	17	16	-8	-11

Note:

This table shows the changes in imports by sector for the share that was transported by air.

6 Conclusion

This paper builds a general equilibrium model of international trade in which production and transportation of goods generate CO_2 emissions and aggravate climate change. Emissions of greenhouse gases are a pure cross-border externality which governments can tax using two environmental policy options. The first is a tax applied over the price of dirty inputs and the second is a tax on international shipments. Our framework is designed to match cross-country and cross-sector data for trade, production and emissions stemming from fossil fuels and different modes of transportation.

We combine our model with input output data from the WIOD (2015a) to compute trade and production in a perfectly green economy with cooperative carbon taxes. Our preliminary findings show that a moderate decrease in emissions by reshuffling world trade patterns of around 20% can lead to a substantial increase in welfare. This comes at the expense of real income which is decreasing in all regions. A future version of this paper will discuss other policies. Additionally, we will implement Negishi (1960) weights into the world welfare formulation and allow the emission intensities of different transport modes to vary.

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Table 6: Elasticity of Substitution

1	Crop and animal production	1.18
2	Forestry and logging	3.04
3	Fishing and aquaculture	1.58
4	Mining and quarrying	1.62
5	Manufacture of food and tobacco	1.97
6	Manufacture of textiles	1.49
7	Manufacture of wood	1.13
8	Manufacture of paper	1.84
9	Printing and media	2.11
10	Manufacture of coke and refined petroleum	5.02
11	Manufacture of chemicals	2.63
12	Manufacture of basic pharmaceuticals	10.16
13	Manufacture of rubber and plastic	2.64
14	Manufacture of other non-metallic minerals	2.38
15	Manufacture of basic metals	2.54
16	Manufacture of fabricated metals	1.88
17	Manufacture of computers	5.89
18	Manufacture of electrical equipment	5.41
19	Manufacture of machinery n.e.c.	6.08
20	Manufacture of motor vehicles	4.97
21	Manufacture of other transport equipment	3.33
22	Manufacture of furniture	4.88
23	Services	5

Note:

This table shows the elasticities of substitution used for the calculation of the counterfactuals. The values stem from Felbermayr et al. (2022).