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Energy Demand and Trade in General Equilibrium

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Abstract This paper sheds light on the impact of alternative environmental policies on energy demand, global CO_2 emissions, trade, and welfare. For this, we develop an Eaton–Kortum type general equilibrium model of international trade which includes an energy sector. We structurally estimate the key parameters of the model and calibrate it to the data on 31 OECD countries and the rest of the world in the year 2000. The model helps assessing the relative welfare effects under alternative environmental policies. We find that, when carbon spillover effects are absent, taxing energy resources as an input in energy production is preferable to taxing domestic energy production in terms of minimizing CO_2 emissions. However, with negative externalities on foreign customers domestic energy output should be taxed to minimize world carbon emissions given a certain level of welfare change for all countries.

Keywords International trade · Energy demand · General equilibrium · Carbon spillovers · Carbon taxes

JEL Classification F11 · F14 · Q43 · Q48

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1 Introduction

The reduction of energy consumption is one of the central issues mankind struggles with in the wake of the twenty-first century. Energy consumption brings about negative externalities on domestic and foreign consumers through emissions and pollution and eventually affects the planet's climate. It is more or less uncontroversial that the world as a whole and some countries in specific have to lower their respective energy consumption levels. The natural question, of course, is which policy instruments would be most efficient in terms of maximizing carbon emission reductions and minimizing welfare losses from distortive taxation.[1]

We tackle this question through the lenses of a structural trade model in the spirit of Eaton and Kortum (2002).[2] This approach adds to the existing literature in several dimensions. First, the calibrated model almost perfectly fits the data in terms of the aggregate income, total carbon emissions, energy endowments and international trade flows. This ensures the plausibility of our comparative statics analysis and sets this model apart from the alternative CGE energy models which typically match the data in fewer dimensions.[3] Second, we introduce a novel way of accounting for negative externalities of CO_2 emissions using the notion of social cost of carbon. Finally, we explicitly include the notion of spatial carbon spillover effects into our analysis which, as we show, are important for carbon tax policy recommendations.

We examine two broad classes of energy taxes, on domestic energy producers versus on the use of energy intensive input. Currently, both forms of taxation are practiced throughout the world. For example, the former tax is broadly consistent with carbon taxes in Denmark, Finland, and France. Japan utilizes the latter form of taxation with taxes on crude oil and coal imported or produced domestically. The central finding of the paper which we explore below is that the former tax would be preferable to the latter in case of spillover effects (i.e., if carbon emissions in one country affect environment globally). The results are reversed when such effects are absent. Hence, cross-border carbon diffusion shapes the set of preferable policy instruments to a considerable degree. The intuition for our result is straightforward. In the absence of cross-border effects, government may tax energy input (such as coal, oil and natural gas), so that domestic energy producers substitute this input with relatively cleaner inputs (e.g., solar and hydro-energy). However, reduction in the domestic demand for CO_2 intensive input drives the world price of that input down thereby increasing demand in the neighboring countries. In the absence of cross-border spillover effects, this has no effect on domestic environment. On the other hand, with environmental spillover effects taxing carbon-intensive input is not optimal because domestic reduction in emissions would be

[1] Already now, many countries provide incentives to reduce energy demand and/or encourage usage of more environmentally friendly technologies. For instance, the *European Union Emission Trading Scheme* (EU ETS) places a green tax on the emitters of relatively high volumes of carbon dioxide within the member countries of the European Union. The United States discuss launching a *Cap and Trade Program* that entails placing an extra cost on producers with polluting technologies.

[2] We choose to use a quantitative workhorse model of international trade in our analysis because energy is central to international trade. An alternative would be to use an energy computable general equilibrium (CGE) model such as Babiker and Rutherford (2005). They employ a multi-country multi-commodity CGE model to study different policy measures such as carbon import tariffs, voluntary export restraints, and carbon taxes on domestic exporters aimed at the reduction of CO_2 and their implications for carbon leakage and welfare.

[3] That energy is at the heart of international trade patterns is an established fact (see Gerlagh and Mathys 2011). Steinbuks and Neuhoff (2010) suggest that one reason for specialization effects of energy demand and supply for trade is the variance of energy input coefficients across sectors. Sato et al. (2007) study the possible effects of the EU's Emissions Trading System (ETS) on industry market shares and profitability. Bridgman (2008) illustrates that international goods transactions involve transport as an energy-intensive activity so that energy price shocks inter alia translate into higher non-tariff trade costs.

compensated by relatively higher demand for carbon-intensive input in other countries. We argue that when such effects are present taxing domestic energy producers, which forces them to substitute away from energy in general (for example investing in energy efficient technologies), is preferable to simply taxing carbon-intensive input.[4]

The remainder of the paper is organized as follows. Section 2 summarizes the model set-up. Section 3 is dedicated to the structural estimation of the model's key parameters and to the calibration. We use the calibrated model to conduct counterfactual experiments in Sect. 4 to shed light on how the energy sector alters the effects of trade liberalization on world general equilibrium and how import tariffs versus taxes on energy production affect welfare and energy demand differently in large as compared to small economies. We summarize the most important results and provide conclusions in the last section.

2 The Model

The purpose of the model is to help us shed light on how the energy sector affects welfare from the viewpoint of consumers and how different policy instruments that can be used to reduce energy demand affect welfare. For this, we distinguish between *energy goods* that are directly consumed by firms and households and *energy resources* that are indirectly consumed, through their use in the production of energy goods rather than through direct consumption. In broad terms, we associate energy goods with refined energy products such as various petroleum products and electricity. Energy resources are commodities such as raw oil and coal which some, but not all, countries are endowed with. Before proceeding to the formal description of the model, it is useful to establish several stylized facts about energy production, energy resource endowments and trade.

1. Energy resource endowments are distributed unequally across economies. Countries can not accumulate and/or produce energy endowments.[5]
2. Trade in energy resources is centralized and the prices of those resources are determined globally. For example, the raw oil market is highly centralized and oil is generally traded at a more or less common world price.
3. The production of energy goods such as electricity and refined petroleum products uses (among other factors) locally available and/or imported energy resources. Energy resources are not directly used in the production of goods or the consumption of households.
4. Energy goods such as electricity and refined petroleum products are traded but much less so than manufacturing goods.
5. Energy production and consumption exerts negative externalities (e.g., through pollution or global warming) not only on domestic but also on foreign consumers.

We incorporate these features of the data into the model in order to study comparative welfare effects of several policy instruments that may be used to reduce energy demand. We follow Eaton and Kortum (2002) and Alvarez and Lucas (2007) in broad terms in considering a

[4] Another possible tax instrument is border tax adjustment. Recently, Elliott et al. (2010) examine the effects of different tax policies on carbon emissions. The authors use a computable general equilibrium model to quantify the comparative effects of different forms of carbon taxes on emissions and conclude that border tax adjustment can be used to completely eliminate carbon leakage induced by a carbon tax on producers. A number of other papers such as Ismer and Neuhoff (2007) or Manders and Veenendaal (2008) also argue that border tax adjustment is an effective measure to eliminate carbon leakage. We choose to focus on two general tax forms and discuss the implications of the border tax adjustment only in the Appendix.

[5] This does not contradict the existence of conservation programs.

multi-country Ricardian model. In our quantitative analysis, we calibrate the model so as to match bilateral and unilateral empirical data for $N = 32$ countries. Of the 32 countries, 31 are individual OECD members and one is a rest of the world.

Each country i is endowed with L_i units of labor which is perfectly mobile between sectors but not across countries. The labor force is employed locally by three different types of firms: a final good producer, intermediate goods producers, and energy producers. This leads to identical wage costs across sectors but not countries. Countries are endowed with a limited supply of a perfectly homogeneous energy resource per capita which is used in the production of energy goods only. We denote country i's aggregate domestic demand for energy resources by $L_i g_{ci}$ and its aggregate endowment by $L_i g_{ei}$. Hence, g_{ci} and g_{ei} are per-capita levels of demand and endowment of energy resources.

Trade occurs in three dimensions. First, countries trade in intermediate goods as in Eaton and Kortum (2002), and Alvarez and Lucas (2007). Second, countries also trade in energy goods. Trade in both intermediates *and* energy goods is subject to sector-specific trade costs. Finally, the homogeneous energy resource is freely tradable at a common world price p_g.

Trade costs at large encompass transaction costs and tariff barriers. We assume that trade is balanced multilaterally and, hence, there is no sector beyond the ones mentioned. Intermediate and energy goods can be used locally only after aggregating them by using a Spence-Dixit-Stiglitz technology (SDS). The corresponding aggregates per capita are referred to as q_i for intermediate goods and as e_i for energy goods hereafter. Households receive positive utility only from consuming the final good. Their budget decreases in (local or global) externalities induced by the production of energy.

2.1 Consumers

Consumers receive utility u_i from final good consumption c_i:

$$u_i(c_i) = c_i. \tag{2.1}$$

Their budget constraint reads

$$p_{ci} c_i \leq l_i w_i + r_i + x_i - f(e_i), \tag{2.2}$$

where p_{ci} is the consumer price of c_i, $l_i w_i$ denotes per-capita income from labor,[6] r_i subsumes total per-capita transfers such as tariff and tax revenues, x_i denotes per-capita revenue from *net* exports of energy resources, and $f(e_i)$ is the dollar-equivalent social cost per consumer in i associated with per-capita energy consumption (with or without cross-border externalities). We will specify $f(e_i)$ below.

We include pollution in the budget constraint rather than the utility function. We consider the former more plausible than the latter, since an individual consumer cannot substitute pollution against consumption of goods and vice versa. This approach is consistent with Copeland and Taylor (2004), who assume that the objective function is to maximize national income subject to a given level of pollution.

2.2 Producers of Intermediate Goods

Producers of differentiated goods produce a unique product per firm j based on a Cobb–Douglas technology with total factor productivity parameter $z_i(j)^{-\theta}$. The latter is drawn for

[6] As in most Ricardian models, we refer to L_i as a primary factor endowment *bundle* in a broad sense. It may either consist of labor in a narrow sense alone or of a bundle of capital, labor in a narrow sense, and other factors (see Alvarez and Lucas 2007, for details). We use l_i to denote the per-capita endowment of L_i.

each country from an exponential distribution with country-specific parameter λ_i. A mass of intermediate firms in i together employs l_{qi}, q_{qi}, and e_{qi} amounts of labor, intermediate input, and energy, respectively, and each of them solves the following profit maximization problem:

$$\max_{l_{qi}(j),q_{qi}(j),e_{qi}(j)} \left\{p_i(j)z_i(j)^{-\theta}l_{qi}(j)^{\epsilon}q_{qi}(j)^{\nu}e_{qi}(j)^{\mu} - p_{qi}q_{qi}(j) - w_i l_{qi}(j) - p_{ei}e_{qi}(j)\right\}, \tag{2.3}$$

where ϵ, ν, and μ are the cost shares for labor, intermediate goods, and energy goods, respectively. Solving the problem yields the equilibrium price for an individual good j:

$$p_i(j) = Az_i(j)^{\theta} w_i^{\epsilon} p_{qi}^{\nu} p_{ei}^{\mu} \quad \text{, where } \Psi_q = \epsilon^{-\epsilon}\nu^{-\nu}\mu^{-\mu}, \quad \epsilon+\nu+\mu = 1. \tag{2.4}$$

Notice that q_{qi} refers to the amount of composite intermediate good q_i devoted to the production of intermediate goods. Accordingly, e_{qi} is the amount of total energy per capita e_i and l_{qi} is the amount of total labor per capita l_i which is used in the intermediate goods sector. The composite production of intermediate goods per capita q_i aggregates all varieties j via the SDS function:

$$q_i = \left(\int_0^{\infty} q_i(j)^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma}{\sigma-1}}, \tag{2.5}$$

where $\sigma > 1$ is the elasticity of substitution between intermediate good varieties. Let $t_{in} \geq 1$ denote an ad-valorem tariff factor that country i places on all the imported intermediate goods from country n and let Y_{qi} denote total demand for intermediate goods by country i. Let π_{in} be the share of Y_{qi} that i spends on intermediate goods from country n. Then, we can formulate respective returns to the factors of production in the intermediate goods sector as:

$$L_i p_{qi} q_{qi} = \nu \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1}; \quad L_i p_{ei} e_{qi} = \mu \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1}; \quad L_i w_i l_{qi} = \epsilon \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1} \tag{2.6}$$

2.3 Producers of Energy

The producer of energy product variety m in country i faces a total factor productivity parameter of $z_e^{-\theta^e}(m)$ drawn from an exponential distribution with mean λ_i^e. Energy producer m uses $l_{ei}(m)$ units of labor per capita (or per unit of the primary factor bundle in general), $q_{ei}(m)$ units of the SDS (intermediate) good per capita, and $g_i(m)$ units of the energy resource input per capita at world price p_g. The optimization problem of a firm producing variety m in country i is:

$$\max_{l_{ei}(m),q_{ei}(m)} \left\{p_{ei}(m)z_{ei}(m)^{-\theta_e}l_{ei}(m)^{\zeta}q_{ei}(m)^{\xi}g_i(m)^{\chi} - w_i l_{ei}(m) - p_{qi}q_{ei}(m) - p_g g_i(m)\right\}. \tag{2.7}$$

The first-order condition yields the usual expression for the price of variety m as in (2.4).

We are interested in comparing different policy instruments that can be utilized to reduce energy demand. Let τ_i denote a flat tax rate placed on the production of *all* energy goods and let κ_i denote a tax rate on the homogeneous energy resource input used in the production of energy goods. In the presence of τ_i and κ_i, the price per unit of energy variety m located in i is:

$$p_{ei}(m) = \Psi_e \tau_i \kappa_i^{\chi} z_i^e(m)^{\theta_e} w_i^{\zeta} p_{qi}^{\xi} p_g^{\chi} \quad \text{, where } \Psi_e = \zeta^{-\zeta}\xi^{-\xi}\chi^{-\chi}, \quad \zeta + \xi + \chi = 1. \tag{2.8}$$

Let $t_{in}^e \geq 1$ denote an ad-valorem tariff factor that i places on all imports of energy products from n and let g_{ci} be the per-capita amount of energy resource input used in the production of energy. As in the case of intermediate producers, we can define total returns to the factors of production for the mass of energy producers as:

$$L_i w_i l_{ei} = \zeta \sum_{n=1}^{N} \pi_{ni}^e Y_{en} (t_{ni}^e)^{-1}; \quad L_i p_{qi} q_{ei} = \xi \sum_{n=1}^{N} \pi_{ni}^e Y_{en} (t_{ni}^e)^{-1};$$
$$\kappa_i L_i p_g g_{ci} = \chi \sum_{n=1}^{N} \pi_{ni}^e Y_{en} (t_{ni}^e)^{-1}. \tag{2.9}$$

Here, '*e*' subscripts and superscripts stand for *e*nergy and represent variables analogous to the ones denoted sub- and superscribed by '*q*' in Eq. (2.6). All energy varieties m are aggregated prior to intermediate and final consumption via the SDS function:

$$e_i = \left(\int_0^{\infty} e_i(m)^{\frac{\rho-1}{\rho}} dm \right)^{\frac{\rho}{\rho-1}}, \tag{2.10}$$

where $\rho > 1$ is the elasticity of substitution between energy good varieties. Admittedly, one could use other functional forms (e.g., Cobb–Douglas) for the aggregation of different energy varieties. However, the assumption of the SDS aggregation is important in this framework to get a well defined analytic solution for trade flows in energy.

2.4 Final Good Producers

Final good producers are perfectly competitive with identical constant returns to scale production functions. They employ l_{ci} units of labor at a wage rate w_i each and use q_{ci} units of the SDS bundle of intermediates and e_{ci} units of energy goods at the respective prices of p_{qi} and p_{ei} to produce c_i units of the final consumption good per capita. They sell their output at a price of p_{ci}. Without loss of generality and for simplicity, assume that there is only one final good producer in each country which solves the following maximization problem involving a Cobb–Douglas technology:[7]

$$\max_{l_{ci}, q_{ci}, e_{ci}} \left\{ p_{ci} l_{ci}^{\alpha} q_{ci}^{\beta} e_{ci}^{\gamma} - w_i l_{ci} - p_{qi} q_{ci} - p_{ei} e_{ci} \right\}, \tag{2.11}$$

where α, β, and γ are Cobb–Douglas cost share parameters for labor, the intermediate goods input bundle, and the energy goods bundle, respectively, as can be seen from the first-order conditions to this problem:

$$\alpha p_{ci} c_i = w_i l_{ci}; \quad \beta p_{ci} c_i = p_{qi} q_{ci}; \quad \text{and} \quad \gamma p_{ci} c_i = p_{ei} e_{ci}. \tag{2.12}$$

[7] Atkeson and Kehoe (1999) assume a constant-elasticity-of-substitution technology and abstract from material inputs to explain cross-section versus time-series patterns in the use of energy.

With perfect competition, the price of the final good is determined as:

$$p_{ci} = \Psi_c w_i^{\alpha} p_{qi}^{\beta} p_{ei}^{\gamma}, \quad \text{where } \Psi_c \text{ is a constant} \quad \text{and} \quad \alpha + \beta + \gamma = 1. \tag{2.13}$$

It would be possible to further extend the model and let countries vary in their productivity in the final goods sector. However, following Alvarez and Lucas (2007) we choose to model production in this sector as in (2.11). More importantly, as we keep all technology parameters constant in our counterfactual analysis, our quantitative analysis would be robust to such extensions.

2.5 Endowment Constraints

The endowment constraints imply that firms in country i exactly employ all L_i; total demand for the energy resource input in the world, $\sum_{i=1}^{N} L_i g_{ci}$, does not exceed total world supply, $\sum_{i=1}^{N} L_i g_{ei}$, and total demands for q_i and e_i do not exceed the respective supplies:

$$L_i(l_{ci} + l_{ei} + l_{qi}) \le L_i; \quad L_i(q_{qi} + q_{ei} + q_{ci}) \le L_i q_i; \tag{2.14}$$
$$L_i(e_{qi} + e_{ci}) \le L_i e_i; \quad \sum_{i=1}^{N} L_i g_{ci} \le \sum_{i=1}^{N} L_i g_{ei}.$$

3 Open-Economy Equilibrium

In an open-economy equilibrium, both intermediate and energy SDS producers in each country may buy inputs around the world.[8] The autarky and trade equilibria differ with respect to the distribution of prices of tradable goods available in each country. Since the parameters θ and θ_e govern the variances of productivity in the intermediate and energy sectors, they play a central role for the magnitude of welfare effects of trade liberalization.

To solve for the large-economy multi-country trade equilibrium, let us start with the distribution of $p_{qi}(j)$ and $p_{ei}(m)$ available in each country at given trade costs. We distinguish between tariffs and other trade cost factors as follows. Assume that tariff revenues from taxing imported intermediates and imported energy products are rebated as a lump-sum transfer to the consumers in i. Let $\{d_{ni}, d_{ni}^e\}$ represent the respective iceberg trade costs for intermediate and energy products, respectively, expressed as the number of units of a good that has to be shipped from n to deliver one unit of that good to i.[9] Given trade costs, i's producers will buy inputs j and m at prices

$$p_{qi}(j) = \min_n \left\{ \Psi_q z_n(j)^{\theta} w_n^{\epsilon} p_{qn}^{\nu} p_{en}^{\mu} d_{ni} t_{in} : n = 1, \ldots, N \right\}, \tag{3.1}$$

$$p_{ei}(m) = \min_n \left\{ \Psi_e \tau_n \kappa_n^{\chi} z_n^e(m)^{\theta_e} (w_n^{\zeta} p_{qn}^{\xi} p_g^{\chi} d_{ni}^e t_{in}^e) : n = 1, \ldots, N \right\}. \tag{3.2}$$

Using the properties of the exponential distribution, we can derive the distribution of prices of intermediate goods and energy goods as follows:

[8] In fact, if we ruled out trade in intermediate goods and energy goods, we could even solve for the closed-economy equilibrium price and quantity vectors analytically. However, the open-economy equilibrium requires numerical solutions under the adopted assumptions, because producers in i will look around for the lowest available $p_{qi}(j)$ for $i = 1, \ldots, N$ and $p_{ei}(m)$ for $i = 1, \ldots, N$ subject to trade costs.

[9] We eliminate all opportunities for arbitrage by making the usual triangular inequality assumption.

$$p_{qi} = \Omega_q \left(\sum_{n=1}^{N} \left[w_n^{\epsilon} p_{qn}^{\nu} p_{en}^{\mu} d_{ni} t_{in} \right]^{-\frac{1}{\theta}} \lambda_n \right)^{-\theta};$$

$$p_{ei} = \Omega_e \left(\sum_{n=1}^{N} \left[w_n^{\zeta} p_{qn}^{\xi} p_g^{\chi} d_{ni}^{e} t_{in}^{e} \right]^{-\frac{1}{\theta_e}} \frac{\lambda_n^e}{(\tau_n \kappa_n^{\chi})^{\frac{1}{\theta_e}}} \right)^{-\theta_e}. \tag{3.3}$$

Here, Ω_q and Ω_e are constants. Solving the system in (3.3) determines the prices of intermediate and energy bundles in each country in terms of wages.

In equilibrium, the world price for energy resources clears the market for endowments. We derive p_g from the world supply and demand for energy resources. First, notice that we express i's demand for energy resources from (2.9) as:

$$\frac{1}{\kappa_i} \frac{\chi}{\zeta} \frac{L_i w_i l_{ei}}{p_g} = L_i g_{ci}. \tag{3.4}$$

Next, notice that total world demand for g can be expressed as $\sum_{i=1}^{N} L_i g_{ci}$:

$$\sum_{i=1}^{N} \frac{1}{\kappa_i} \frac{\chi}{\zeta} \frac{L_i w_i l_{ei}}{p_g} = \sum_{i=1}^{N} L_i g_{ci}. \tag{3.5}$$

The world price of energy resources is determined by total demand and supply. Total world supply of g can be inferred from the observation on energy resource endowments, $\sum_{i=1}^{N} L_i g_{ei}$. With the latter information at hand, we can derive the world price of g as:

$$p_g = \frac{\chi}{\zeta} \frac{\sum_{i=1}^{N} L_i w_i l_{ei} \kappa_i^{-1}}{\sum_{i=1}^{N} L_i g_{ei}}, \tag{3.6}$$

where $L_i l_{ei}$ is an aggregate primary factor (labor) employment in the energy sector of country i, and $L_i w_i l_{ei}$ is the aggregate wage bill in that country and sector.

With all factor prices expressed in terms of wages, we may solve for w_i by utilizing each country's multilateral trade balance condition which closes the model. Since there is a mass of varieties of intermediate and energy goods, the probability for country i to buy good j from country n equals the share of i's income spent on goods from n. These shares π_{in} and π_{in}^e equal the probability that $p_n(j)$ and $p_e(m)$ are lowest among all n subject to bilateral trade costs and tariffs. Hence, we can specify trade flows from n to i normalized by total expenditures of consumers in i in the same sector as follows:

$$\pi_{in} = \Omega_q^{-\frac{1}{\theta}} \lambda_n \left(\frac{w_n^{\epsilon} p_{qn}^{\nu} p_{en}^{\mu} t_{in} d_{ni}}{p_{qi}} \right)^{-\frac{1}{\theta}}; \quad \pi_{in}^e = \Omega_e^{-\frac{1}{\theta}} \frac{\lambda_n^e}{(\tau_n \kappa_n^{\chi})^{\frac{1}{\theta_e}}} \left(\frac{w_n^{\zeta} p_{qn}^{\xi} p_g^{\chi} d_{ni}^{e} t_{in}^{e}}{p_{ei}} \right)^{-\frac{1}{\theta_e}}, \tag{3.7}$$

where Ω_q and Ω_e are constants.

Beyond intermediate goods and energy goods, there is trade in energy resources. We assume multilaterally balanced trade so that total spending on imports equals total earnings from exporting. To state this relationship formally, it is useful to define a set of aggregate variables. In particular, let $L_i w_i = V_i$ (aggregate primary factor income), $L_i r_i = R_i$ (aggregate transfers from taxes and tariffs), $L_i x_i = X_i$ (aggregate net exports of energy resources). For later reference, let us also define $L_i e_i = E_i$ (aggregate energy demand) and $L_i c_i = C_i$ (aggregate final goods demand).

At this point, let us define two additional parameters of the model—s_q and s_e—that represent shares of spending on intermediate and energy goods, respectively, in final consumption.

Let Y_i be aggregate spending of i. Then, $s_q Y_i$ and $s_e Y_i$ represent aggregate spending on intermediates and energy goods in i, respectively. This, in turn, can be specified as the sum of demands for intermediates and energy products of the final, intermediate, and energy producers together:

$$Y_{qi} \equiv s_q Y_i = L_i w_i \left(\frac{\beta}{\alpha} l_{ci} + \frac{\xi}{\zeta} l_{ei} + \frac{\nu}{\epsilon} l_{qi} \right); \quad Y_{ei} \equiv s_e Y_i = L_i w_i \left(\frac{\gamma}{\alpha} l_{ci} + \frac{\mu}{\epsilon} l_{qi} \right) \quad (3.8)$$

Because of the revenues generated by valued net exports of energy resources X_i as well as total transfers R_i comprised of tax and tariff revenues, the values of production and consumption are not proportional in this model. To close the model we assume that total trade is balanced,[10] i.e., total imports of intermediate *and* energy goods equal to the sum of total exports inclusive of net energy resource exports:

$$(s_q + s_e)(V_i + X_i + R_i) = \sum_{n=1}^{N} (\pi^q_{ni} s_q + \pi^e_{ni} s_e)(V_n + X_n + R_n). \quad (3.9)$$

Hence, in this model GDP consists of total value added, $L_i w_i$, revenues from net exports of energy resources, X_i, and total tariff revenues, R_i. Let us also specify $X_i = Y^e_{gi} - Y^c_{gi}$, where Y^e_{gi} is total dollar value of i's resource endowment and Y^c_{gi} is the total dollar value of the endowment consumed by i.

We use (3.9) for all countries to solve for w_i. The algorithm is discussed in more details in the coming sections.

4 Estimation

In this section, we directly estimate technology dispersion parameters θ and θ_e. We discuss the calculation of the remaining parameters $\{\alpha, \beta, \gamma, \epsilon, \nu, \mu, \zeta, \xi, \chi\}$ in the Appendix. All parameters are estimated in a model-consistent way.

For measurement of π_{in}, we use data from the OECD's STAN Industry Database and the STAN Bilateral Trade Database from the Organization for Economic Cooperation and Development, Statistical Database (2010). In particular, we employ data on trade and production in agriculture and manufacturing at large. We define π_{in} as the ratio of nominal exports from n to i in the numerator (from OECD's STAN Bilateral Trade Database) and the total absorption capacity of i in agriculture and manufacturing in the denominator (from OECD's STAN Industry Database). The latter equals total output plus net imports in agriculture and manufacturing.

To measure tariffs t_{in} and t^e_{in}, we use sectoral (agriculture and manufacturing on the one hand and energy on the other hand) averages from Mayer et al. (2008). We employ those data together with fixed exporter-specific effects and two variables from the Centre d'Études Prospectives et d'Informations Internationales' (CEPII) geographical database—a common land border indicator variable (adjacency) and bilateral distance between countries' economic centers—to formulate trade costs.

The data on GDP and CO_2 emissions originate from the World Bank's World Bank Development Indicators Database (2010). The input–output tables utilized to estimate production

[10] It is straightforward to follow Dekle et al. (2007) and assume that trade is balanced up to some constant D_i which captures the observed trade deficit of country i. We, however, choose to assume perfectly balanced trade as the counterfactual value of D_i would be exogenous and not have a structural interpretation in the context of our analysis.

and consumption parameters are from OECD's STAN input–output tables. The reference year of all data is 2000.

4.1 Technology Dispersion Parameters

In order to estimate the two parameters θ and θ_e that govern the dispersion of technologies between countries, we use the trade flow equations. We modify them by dividing π_{in} and π^e_{in} by the respective home sales π_{ii} and π^e_{ii}. Hence, we employ a stochastic version of the following equation to estimate θ:

$$\frac{\pi_{in}}{\pi_{ii}} = \left(\frac{\lambda_n^{-\theta} w_n^{\epsilon} p_{qn}^{\nu} p_{en}^{\mu}}{\lambda_i^{-\theta} w_i^{\epsilon} p_{qi}^{\nu} p_{ei}^{\mu}}\right)^{-\frac{1}{\theta}} (t_{in} d_{ni})^{-\frac{1}{\theta}}. \tag{4.1}$$

Of course, trade costs d_{ni} and d^e_{ni} are unobservable. We specify them as follows as a multiplicative function as is common in the literature:

$$log(d_{ni}) \equiv \log\frac{\pi_{in}}{\pi_{ii}} = ex_n + \iota adjacency_{in} + \sum_{k=1}^{6} \beta_k d_{k,ni}, \tag{4.2}$$

$$log(d^e_{ni}) \equiv \log\frac{\pi^e_{in}}{\pi^e_{ii}} = ex^e_n + \iota_e adjacency_{in} + \sum_{k=1}^{6} \beta^e_k d_{k,ni}, \tag{4.3}$$

where ex_n and ex^e_n are fixed exporter-specific effects for country n in the two sectors, $adjacency_{in}$ is an indicator variable which is unity whenever two countries share a common land border, $d_{k,in}$ is an indicator variable which is unity if the distance between two countries lies in the kth sextile of the distance distribution, and ι and β_k as well as ι_e and β_{ek} are unknown parameters. Then, we can rewrite Eq. (4.1) in logs as:

$$\tilde{\pi}_{in} = c_i - c_n - \frac{1}{\theta}\left(log(t_{in}) + ex_n + \iota adjacency_{ni} + \sum_{k=1}^{K} \beta_k d_{k,ij}\right), \tag{4.4}$$

where $c_i - c_n$ is the difference in symmetric exporter- and importer-specific effects so that ex_n measures the deviation of asymmetric exporter-specific trade costs from symmetric ones (see Eaton and Kortum 2002; Waugh 2010). The corresponding equation for the energy sector is:

$$\tilde{\pi}^e_{in} = c^e_i - c^e_n - \frac{1}{\theta_e}\left(log(t^e_{in}) + ex^e_n + \iota_e adjacency_{ni} + \sum_{k=1}^{K} \beta^e_k d_{k,ij}\right). \tag{4.5}$$

Notice that we can estimate θ and θ_e using tariffs as the only observable ad-valorem trade cost factors.[11] We estimate (4.4) and (4.5) using fixed effects subject to the constraints that $c_i = c_n$ and $c^e_i = c^e_n$ whenever $i = n$.

We measure π^e_{in} as an aggregate of the following categories in OECD's STAN Industry Database:

- Coke, refined petroleum products, and nuclear fuel.
- Production, collection, and distribution of electricity.
- Manufacture of gas; distribution of gaseous fuels through mains.

[11] Independently, Caliendo and Parro (2010) developed another way to estimate θ from the data on tariffs.

Table 1 Estimating parameters θ and θ_e

	Intermediate		Energy	
Variable	Coef.	Std. error	Coef.	Std. error
t_{in}	−4.297	1.065	–	–
t^e_{in}	–	–	−11.054	1.779
Adjacency	0.221	0.113	0.583	0.156
$\ln(distance)$:				
$[\ln min, \ln 375)$	−3.419	0.091	−7.345	0.167
$[\ln 375, \ln 750)$	−3.909	0.055	−7.365	0.149
$[\ln 750, \ln 1500)$	−4.033	0.052	−8.322	0.195
$[\ln 1500, \ln 3000)$	−4.301	0.070	−8.349	0.107
$[\ln 3000, \ln 6000)$	−4.551	0.109	−8.395	0.135
$[\ln 6000, \ln max)$	−4.553	0.109	−8.513	0.138
Pseudo-R^2	0.710	–	0.885	–
Num. of observations	1,056	–	1,056	–

The reported standard errors are based on Eicker–White sandwich estimates. The reported Pseudo-R^2 corresponds to the correlation between observed and predicted values of the dependent variable. Country-specific fixed effect coefficients are suppressed

- Steam and hot water supply.
- Collection, purification, and distribution of water.[12]

Estimating (4.4) and (4.5) in a nonlinear fashion is preferable over estimating it in a log-linear way for two reasons. First, zeros are not eliminated so that a sample selection bias from dropping observations is avoided. Second, one can avoid inconsistent marginal effects accruing to mis-specification of the stochastic process as log-additive versus level-additive when using a Poisson pseudo-maximum-likelihood (PML) model with robust standard errors (see Santos Silva and Tenreyro 2006).[13] We summarize Poisson PML model estimates for (4.4) and (4.5) in Table 1.

Our coefficients on distance and adjacency are consistent with the structural gravity literature. Recall that the coefficient on t_{in} corresponds to $-\theta^{-1}$. Hence, we can infer that $\theta \simeq -\dfrac{1}{-4.30} \simeq 0.23$ and $\theta_e \simeq -\dfrac{1}{-11.05} \simeq 0.09$ respectively. XXX Our estimate of θ falls comfortably in the range of the estimates of Eaton and Kortum (2002) who estimate it to be between 0.08 and 0.27 and the values adopted by Alvarez and Lucas (2007) who use three alternative values ranging from 0.1 to 0.25. The result is also consistent with the ones in Waugh and Simonovska (2010), who use a method of simulated moments estimator and estimate θ to be between 0.23 and 0.4. Interestingly, the estimate of θ_e is considerably

[12] It is impossible to avoid some degree of measurement error when defining certain goods as energy and others not. However, the strong reliance of these five sectors on raw energy endowment resource inputs such as coal, oil, etc., suggests that these sectors can be classified as energy producers in the sense of the model. Obviously, among the five sectors the *Collection, purification, and distribution of water* is not directly an energy producer. But it is an important intermediate input to goods production, and it is very energy intensive according to input–output tables. So, for quantification it appears reasonable to subsume it under the category of energy resource users and energy producers.

[13] As an exponential-family multiplicative estimator, PML differs from non-linear least squares only by way of weighting the data.

lower than that of θ. This is consistent with the results in Caliendo and Parro (2010) who estimated a lower value of θ for refined petroleum relative to manufacturing products. The intuition behind this result is that energy goods are much more homogeneous in comparison to intermediate goods at large. Accordingly, the observed productivity dispersion should be lower as well.

5 Calibration

One of the challenges in calibrating Eaton and Kortum (2002) type models is the estimation and specification of endowments L_i, technology parameters λ_i, and trade costs d_{ni} and d^e_{ni}. To abstain from making strong assumptions on these variables, we express and analyze the model in relative changes as suggested by Dekle et al. (2007). In particular, we assume that endowment, technology and trade costs parameters are primitives of the model and do not change in any considered counterfactual experiment. Perhaps, it is instructive to consider an example. Recall that trade flows in intermediate goods can be expressed as:

$$\pi_{in} = \Omega_q^{-\frac{1}{\theta}} \lambda_n \left(\frac{w_n^{\epsilon} p_{qn}^{\nu} p_{en}^{\mu} t_{in} d_{ni}}{p_{qi}} \right)^{-\frac{1}{\theta}}. \tag{5.1}$$

Let us rewrite this expression in relative changes. Let a' denote the counterfactual value of some variable a and let $\widehat{a} = a'/a$. Hence, $\hat{a}$ is a relative change of a compared to its benchmark value. In any counterfactual experiment (5.1) can be expressed in relative changes such that:

$$\widehat{\pi}_{in} = \widehat{\lambda}_n \left(\frac{\widehat{w}_n^{\epsilon} \widehat{p}_{qn}^{\nu} \widehat{p}_{en}^{\mu} \widehat{t}_{in} \widehat{d}_{ni}}{\widehat{p}_{qi}} \right)^{-\frac{1}{\theta}}. \tag{5.2}$$

The assumption that primitives are constant entails $\widehat{\lambda}_n = 1$ and $\widehat{d}_{ni} = 1$ so that (5.2) simplifies to

$$\widehat{\pi}_{in} = \left(\frac{\widehat{w}_n^{\epsilon} \widehat{p}_{qn}^{\nu} \widehat{p}_{en}^{\mu} \widehat{t}_{in}}{\widehat{p}_{qi}} \right)^{-\frac{1}{\theta}}. \tag{5.3}$$

Furthermore, observing π_{in} we can solve for counterfactual π'_{in} as:

$$\pi'_{in} = \pi_{in} \left(\frac{\widehat{w}_n^{\epsilon} \widehat{p}_{qn}^{\nu} \widehat{p}_{en}^{\mu} \widehat{t}_{in}}{\widehat{p}_{qi}} \right)^{-\frac{1}{\theta}}. \tag{5.4}$$

The advantage of this approach is that we can conduct counterfactual experiments without estimating *unobservable* primitives of the model and without having to solve for (observable) π_{in} as a function of those primitives. We express the model in relative changes in Table 2.

Before proceeding to counterfactuals we need to calibrate the model with particular emphasis on energy resource endowments and energy demand. First, we have to map energy resource endowments (a stock) as observed in the data and discussed in the next subsection into an energy resource input (a flow) in the model. Second, we need to examine the fit of the model calibration against the data in several dimensions, including energy usage. Finally, we need to specify the functional form of energy consumption and its negative (local versus global) externalities on consumers, $f(e_i)$. The latter is vital for a welfare analysis of the suggested policy instruments.

Table 2 Expressing the model in relative changes

Variable	Benchmark	Counterfactual
Y_i	$Y_i = V_i + X_i + R_i$	$Y_i' = V_i' + X_i' + T_i'$
V_i	$V_i = L_i w_i$	$V_i' = \widehat{w}_i V_i$
X_i	$X_i = Y_{gi}^e - Y_{gi}^c$	$X_i' = \widehat{p}_g Y_{gi}^e - \frac{\widehat{w}_i}{\widehat{\kappa}_i} Y_{gi}^c$
R_i	$R_i = R_{qi} + R_{ei} + R_{ki} + R_{ti}$	
R_{qi}	$R_{qi} = (t_{in} - 1) \sum_{n=1}^N \pi_{in} s_q Y_i$	$R_{qi}' = (t_{in}' - 1) \sum_{n=1}^N \pi_{in}' s_q Y_i'$
R_{ei}	$R_{ei} = (t_{in}^e - 1) \sum_{n=1}^N \pi_{in}^e s_e Y_i$	$R_{ei}' = (t_{in}'^e - 1) \sum_{n=1}^N \pi_{in}'^e s_e Y_i'$
R_{ki}	$R_{ki} = (\kappa_i - 1) Y_{gi}^c$	$R_{ki}' = \frac{(\kappa_i' - 1)\widehat{w}_i}{\widehat{\kappa}_i} Y_{gi}^c$
R_{ti}	$R_{ti} = (\tau_i - 1) s_e V_i$	$R_{ti}' = (\tau_i' - 1) s_e V_i'$
π_{in}	$\pi_{in} = \Omega^{-\frac{1}{\theta}} \lambda_n \left(\frac{w_n^\epsilon p_{qn}^\nu p_{en}^\mu t_{in} d_{ni}}{p_{qi}} \right)^{-\frac{1}{\theta}}$	$\pi_{in}' = \pi_{in} \left(\frac{\widehat{w}_n^\epsilon \widehat{p}_{qn}^\nu \widehat{p}_{en}^\mu \widehat{t}_{in}}{\widehat{p}_{qi}} \right)^{-\frac{1}{\theta}}$
π_{in}^e	$\pi_{in}^e = (\Omega^e)^{-\frac{1}{\theta}} \frac{\lambda_n^e}{(\tau_n \kappa_n^\chi)^{\frac{1}{\theta^e}}} \left(\frac{w_n^\zeta p_{qn}^\xi p_g^\chi d_{ni}^e t_{in}^e}{p_{ei}} \right)^{-\frac{1}{\theta^e}}$	$\pi_{in}'^e = \pi_{in}^e \left(\frac{\widehat{w}_n^\zeta \widehat{p}_{qn}^\xi \widehat{p}_g^\chi \widehat{t}_{in}^e \widehat{\tau}_n \widehat{\kappa}_n^\chi}{\widehat{p}_{ei}} \right)^{-\frac{1}{\theta^e}}$
p_{qi}	$p_{qi} = \Omega \left(\sum_{n=1}^N \left[w_n^\epsilon p_{qn}^\nu p_{en}^\mu d_{ni} t_{in} \right]^{-\frac{1}{\theta}} \lambda_n \right)^{-\theta}$	$\widehat{p}_{qi} = \left(\sum_{n=1}^N \pi_{in} (\widehat{w}_n^\epsilon \widehat{p}_{qn}^\nu \widehat{p}_{en}^\mu \widehat{t}_{in})^{-\frac{1}{\theta}} \right)^{-\theta}$
p_{ei}	$p_{ei} = \Omega^e \left(\sum_{n=1}^N \left[w_n^\zeta p_{qn}^\xi p_g^\chi d_{ni}^e t_{in}^e \right]^{-\frac{1}{\theta^e}} \frac{\lambda_n^e}{(\tau_n \kappa_n^\chi)^{\frac{1}{\theta^e}}} \right)^{-\theta^e}$	$\widehat{p}_{ei} = \left(\sum_{n=1}^N \pi_{in}^e (\widehat{w}_n^\zeta \widehat{p}_{qn}^\xi \widehat{p}_g^\chi \widehat{t}_{in}^e \widehat{\tau}_n \widehat{\kappa}_n^\chi)^{-\frac{1}{\theta^e}} \right)^{-\theta^e}$
p_g	$p_g = \frac{\chi}{\zeta} \frac{\sum_{i=1}^N L_i w_i l_{ei} \kappa_i^{-1}}{\sum_{i=1}^N L_i g_{ei}}$	$\widehat{p}_g = \frac{\sum_{i=1}^N Y_{gi}^c \widehat{w}_i (\widehat{\kappa}_i)^{-1}}{\sum_{l=1}^N Y_{gi}^c}$

5.1 Calibrating Energy Endowments

A relatively good measure of energy resource endowment stock is a country's proven reserves of oil, natural gas, coal, etc. Data on such endowment stocks are available from the U.S. Energy Information Administration. The data, however, come in different units and, most importantly, reflect stocks (i.e., an integral of currently and potentially in the future usable inputs) rather than flows. Hence, those data can not be used directly in a framework as ours. However, ex ante, total output of the sector *Mining and quarrying of energy resources* across all countries should be proportional to total energy resource endowments on the globe. Then, on average, the output of the energy mining sector in a country should be a good measure of a country's energy resource endowment. This can be assessed when comparing the output of this sector to the proven reserves of energy resource endowments relative to, say, the United States.

To calculate the endowment of energy resources, we use data on proven oil and natural gas reserves as of 2000 and convert the respective values into British Thermal Units (BTUs).[14] So, total reserves in country i are simply the sum of proven oil and natural gas reserves. We then compare how well we can match (or explain) these data on energy resource endowments (stocks) by using total output of the energy mining sector (flows).

Without loss of generality, we assume that one dollar of output in the energy mining sector corresponds to one unit of endowment in the current framework. Hence, we correlate data on $L_i g_{ei}$ measured as total output of the energy mining sector with energy endowment PR_i

14 We omit endowments of coal due to data limitations.

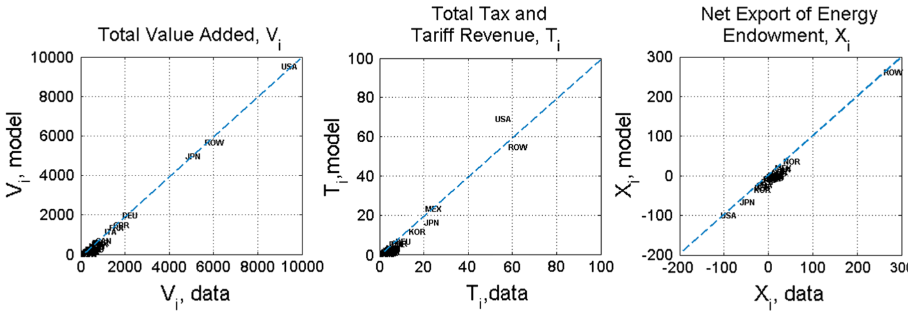

Fig. 1 Fit of calibration (in billion U.S. dollars)

as measured by total Proven Reserves. Even though there are some outliers (mainly over-extracting Norway and under-extracting Mexico) the correlation between the two measures is very strong. In the total sample, the correlation coefficient amounts to 0.66 and when excluding Norway and Mexico it is as high as 0.97. Hence, we conclude that the proposed metric is plausible to convert stocks of (valued or unvalued) energy resource inputs into flows on average.

5.2 Fit of Calibration

To check the fit of the calibration, we compare *data* on key endogenous variables such as an economy's total value added V_i, its total tax and tariff revenues R_i (i.e., at given tariff rates this implicitly means comparing import levels), and net exports of the energy resource inputs X_i with *model predictions*.

Since we resort to the approach advocated by Dekle et al. (2007) we assess all features in relative terms as described above.[15] Such a comparison can tell us to which extent the above estimated parameters and data on exogenous variables are useful to talk about real economies based on the proposed stylized model. The fit of calibration in terms of the key variables is summarized in Fig. 1. The panels in Fig. 1 suggest that the model predicts the data extraordinarily well. The correlation coefficient between actual and predicted values is close to unity in every dimension considered.

5.3 Quantifying the Negative Effect of Energy Production

For a welfare assessment of policy variables we need to specify how energy consumption—and the associated emissions—affect welfare. Technically, this involves specifying the functional form of $f(e_i)$ in the income constraint (2.2). We use the latter to capture direct benefits from a reduction of energy consumption in contrast to economic costs from doing so. Quantifying the welfare costs of energy consumption is admittedly not straightforward. To simplify matters somewhat, we choose to concentrate on carbon emissions that energy production entails. Specifically, we resort to the concept of the social cost of carbon (SCC) to convert carbon emissions into an equivalent dollar value. Clarkson and Deyes (2002) represent an important reference in this respect. They provide an excellent survey on the methodology

[15] Technically, we assess the fit of calibration by shocking each outcome by a vector of zeros for all countries and comparing the outcome between the data and the model. Based on the obtained results, we can then recover counterfactual values of V_i, R_i, and X_i, in absolute dollar values. We provide a detailed description of how to solve the model in counterfactual equilibrium in the next section.

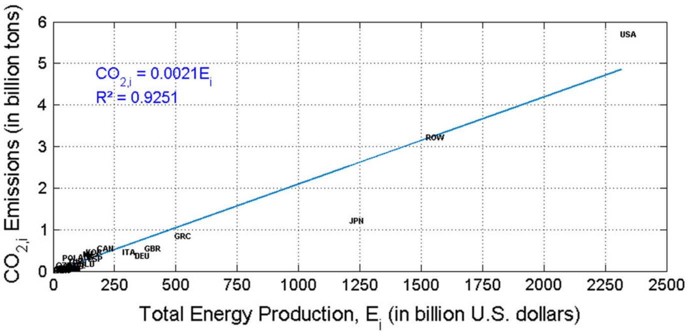

Fig. 2 Total CO_2 emissions (data) versus total energy production (model)

behind and estimates of the SCC. The range of the estimates they report is quite wide. Thus, we will use an interval to capture the degree of uncertainty in that regard. Ayres and Walter (1991) suggest a lower bound of roughly 35 U.S. dollars per ton of CO_2. The upper bound of 125 U.S. dollars per ton of CO_2 is supported in a recent study of Ackerman and Stanton (2011).

Quite obviously, the marginal price of carbon increases with time, consistent with a greater accumulation of carbon in the atmosphere. Therefore, we model $f(E_i) = f(L_i e_i)$ as an increasing function of energy. When specifying $f(E_i) = f(L_i e_i)$ such that its level reflects country i's level of CO_2 emissions, $f(\cdot)$ is some continuous function, and ω is the SCC scaling factor, the consumer's problem becomes:

$$u_i(c_i) = c_i \quad \text{such that} \quad p_{ci} c_i \le x_i + r_i + w_i - (\omega f(CO_{2,i})). \tag{5.5}$$

This approach is similar to that of Copeland and Taylor (2003, 2004), who assume that pollution is a required input in a Cobb–Douglas production function. The difference is that we model a separate energy sector and assume that (intermediate and final) consumption of energy is proportional to pollution.

We use data from the World Bank's World Development Indicators on CO_2 emissions for the year 2000. We then regress benchmark values of total aggregate energy output, $E_i = L_i e_i$, on CO_2 emissions. The results are summarized in Fig. 2, suggesting two conclusions. First, production of energy is clearly proportional to CO_2 emissions on average so that $f(CO_{2,i})$ is linear in its argument. Second, the model is able to predict total energy production quite accurately. Figure 2 suggests that

$$f(E_i) = 0.0021 E_i. \tag{5.6}$$

The consumer's problem in (5.5) can then be written as:

$$u_i(C_i) = C_i \quad \text{such that} \quad p_{ci} C_i \le X_i + R_i + V_i - (\omega f(E_i)) \quad \text{for} \quad \omega \in [35, 125], \tag{5.7}$$

Notice that we could express (5.5) in per-capita terms. However, since consumers are homogeneous, the results in per-capita and aggregate terms are identical. Real consumption for the whole economy, $C_i = L_i c_i$, can then be stated as

$$C_i = \frac{V_i + R_i + X_i - w f(E_i)}{p_{ci}} \quad \text{for} \quad \omega \in [35, 125]. \tag{5.8}$$

6 Counterfactuals

This section is concerned with a quantification of the relative welfare effects of the mentioned more or less direct policy instruments aimed at reducing a country's energy demand. The two instruments considered are: a tax on the domestic energy production at large (τ_i which is a direct instrument);[16] and a tax on the usage of the energy resource input (κ_i which is an indirect instrument). Admittedly, our framework does not capture dynamic effects of directed technical change towards cleaner technologies (see Acemoglu et al. 2012). It rather quantifies comparative statics effects for aggregate economies and abstains from the discussion of a dynamic adoption of cleaner technologies.

Recall that hats denote relative changes of variables throughout and a prime indicates a counterfactual value of a variable. Then, using notation in an obvious way, an exogenous change in tax and/or tariff rates changes (3.9) to:

$$(s_q + s_e)(V_i' + X_i' + T_i') = \sum_{n=1}^{N} (\pi_{ni}' s_q + \pi_{ni}'^{e} s_e)(V_n' + X_n' + T_n'). \qquad (6.1)$$

Recall that $V_i = L_i w_i$ so that we can express $V_i' = L_i w_i'$ or $V_i' = V_i \widehat{w}_i$. We can express all other variables in (6.1) in the same manner. Table 2 summarizes benchmark and counterfactual values using this insight.

Hence, in the counterfactual exercises we solve for counterfactual *changes* ($\widehat{w}_i$) rather than *levels* (w_i') of wages, given benchmark and counterfactual values of policy instruments (in particular, τ_i and κ_i). While we would be able to principally discuss changes in t_{in} and t_{in}^e, we largely suppress this discussion and keep those instruments constant for the sake of brevity. These instruments enter the problem in different ways and may reduce energy demand with different welfare consequences. In what follows, we will quantify these comparative welfare effects. Countries differ in their trade costs (for intermediate goods or energy), factor endowments (including energy resources), and technology. These differences lead to different responses to the policy instruments. Hence, it is important to consider responses in individual countries. While we always solve the model for all 32 economies, we single out Australia, Belgium, Norway, and the United States to discuss the responses in outcome in detail. These countries differ dramatically in their remoteness and size and, hence, in their openness. Moreover, they differ in the local access to energy resources.

6.1 Counterfactual Experiment: τ_i Versus κ_i to Reduce Emissions of CO_2

A commitment of countries to international treaties such as the Kyoto Protocol and the Copenhagen Accord requires them to consider a reduction of pollution through the use of domestic policy instruments. Higher taxes on domestic producers increase their average marginal costs and affect firms' competitiveness. These effects may be large.[17] In the experiment, we look at

[16] Notice that energy production generates an input which is local in nature in the sense that intermediate goods producers can not *escape* local supply by directly importing from abroad. However, the energy bundle is and corresponding prices are aggregated as indicated in (2.8). Therefore, a tax on local energy production imposes some discrimination of domestic energy producers in comparison to foreign energy producers from the perspective of domestic energy demand. Notice, however, that trade in energy goods is extremely limited to begin with. This is due to high trade costs. For example, it would be very costly to transport one unit of electricity from France to the United States. Hence, the problem of domestic discrimination is relatively minor.

[17] For example, Felbermayr and Aichele (2012) use matching econometrics and show that countries, who committed to a reduction of pollution under the Kyoto protocol experienced a reduction in their exports of approximately 13–14 %.

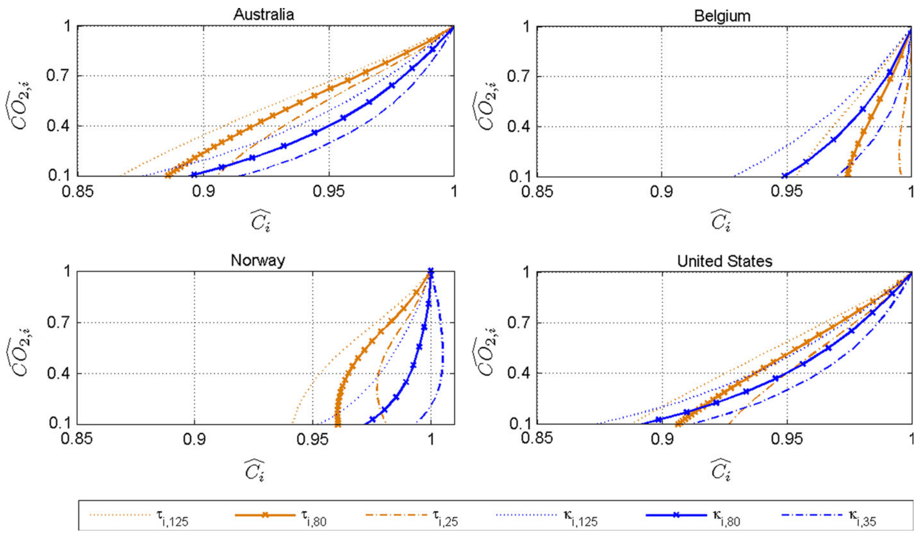

Fig. 3 Energy demand versus welfare

different policy instruments that can be used to reduce CO_2 emissions through reducing the demand for energy. Specifically, we vary τ_i (the flat tax rate on the production of all energy goods) and κ_i (tax rate on the homogeneous energy resource input) and compare the induced change in CO_2 emissions given equal change in real welfare. We first assume that spillover effects are absent such that each country fully internalizes its own carbon emissions.

In Fig. 3, we plot the welfare change in real terms, $\widehat{C}_i$, against a given level of reduction in CO_2 emissions for Australia, Belgium, Norway, and the United States. Since we use the interval for the social cost of carbon (SCC; reflected by ω) we plot three different lines for each instrument. The solid lines in Fig. 3 refer to the average level of $\omega = 80$, and the broken lines refer to the upper and lower bound of the interval ($\omega = 35$ and $\omega = 125$, respectively). In each of the four panels, we consider two tax instruments τ_i and κ_i.

The results in Fig. 3 illustrate two tendencies. First, the response of real welfare and energy demand to the two types of taxes is heterogeneous across countries. Second, among the two instruments, the tax on energy resource inputs induces relatively larger reductions in CO_2 emissions in i at a given real welfare change than the tax on energy goods. The exception is Belgium, which relies heavily on imported energy resources. Hence, it takes advantage by importing energy goods without having to face large negative economic effects from a tax on the local production of energy. On the other hand, Australia, Norway, and the United States maximize the reduction in domestic CO_2 emissions subject to the given level of change in real welfare by employing the energy resource tax κ_i rather than τ_i. Hence, the results also depend on the size of the resource endowment in each country. Countries with low resource endowment (such as Belgium) depend relatively more on imports of energy resources from other countries such that an equivalent tax on energy resource inputs induces larger reductions in carbon emissions, whereas energy resource-abundant countries react more sensitively to taxes on energy production.

In general, the difference between the two measures in terms of a reduction of emissions could be quite large. For example, Fig. 3 indicates that given a 5 % reduction in real welfare and $\omega = 80, \kappa_i$ reduces emissions by 60 %, and τ_i reduces them by only around 40 %

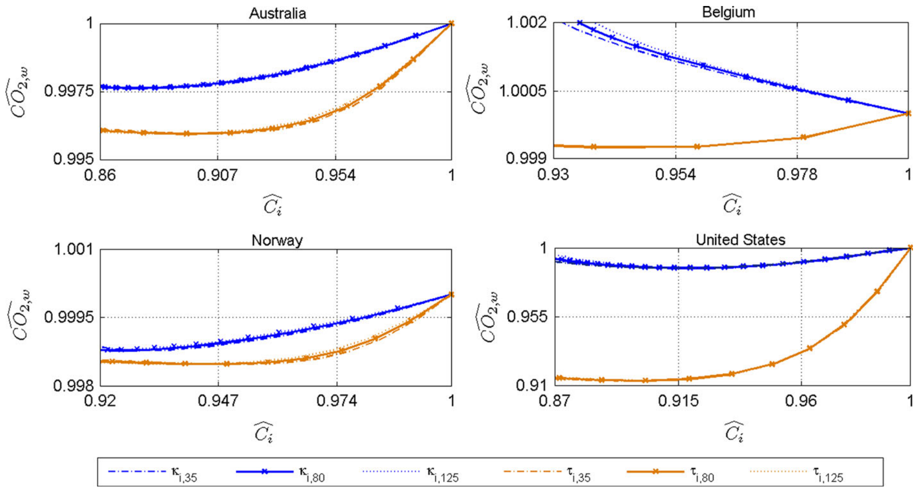

Fig. 4 Energy demand versus welfare

in Australia. The intuition for this result is as follows. Taxes κ_i and τ_i work on different substitution margins. The former tax, κ_i, makes energy producers in i substitute away from carbon-intensive inputs and use relatively cleaner energy sources (an intuitive example would be using solar and wind energy), however, firms in the intermediate and final goods sectors do not substitute away from energy as an input. The latter tax, τ_i, on the other hand, forces firms in the intermediate and final goods sectors to substitute away from energy towards other factors (e.g., this would mean investing more into energy-efficient technologies).

The results in Fig. 3 are conditional on the assumption of no spillover effects. The results offer an explanation of why Japan employs an oil and coal tax rather than indirect carbon tax. Japan is a relatively remote country that might be able to avoid some of the negative externalities from carbon consumption in other countries (except for China). This is certainly not the case for countries in Europe where cross-border effects should be much stronger. Accordingly, Denmark, Finland, France, Switzerland and a handful of other European countries employ carbon taxes. We show below that the model here is consistent with these patterns.

Emissions of CO_2 affect the world climate so that energy production in one country is likely to have detrimental effects on other countries in the world. Let us suppose that countries care about the *global* rather than the *national* level of CO_2 emissions which is quite plausible. The consumer's problem then becomes:

$$u_i(C_i) = C_i \quad \text{such that} \quad p_{ci}C_i \leq X_i + R_i + V_i - \frac{Y_i}{Y_w} f(E_w) \tag{6.2}$$

Here, E_w refers to the world-wide level of CO_2 emissions. Y_i and Y_w refer to i's and the world's nominal GDP in the benchmark equilibrium. Hence, we assume that CO_2 costs are distributed proportionately to countries' size in terms of Y_i.[18]

In Fig. 4, we display changes in real welfare versus changes in global emissions of CO_2 for the same four countries as before. Figure 4 suggests that, once we allow for negative externalities of energy to have an effect on foreign consumers, taxing energy resource inputs in

[18] This assumption is not crucial for our results. We could alternatively calculate shares as a function of L_i. We choose the former approach because we do not observe L_i directly in the Ricardian model with a bundle of production factors.

energy production is no longer an optimal policy in terms of minimizing world CO_2 emissions. In particular, τ_i dominates κ_i in terms of conditionally minimizing the level of world CO_2 emissions for all countries. Hence, the internalization of cross-border externalities flowing from energy production and consumption reverses the earlier conclusions. The reason for this is the so-called *carbon leakage*, a major concern in environmental policy making. Carbon leakage implies that reducing energy demand in i does not necessarily lead to a reduction in world CO_2 emissions, if other countries do not impose the same policies. For instance, if the United States were to impose a restrictive environmental policy, their competitors would be reluctant to follow and rather increase their consumption of carbon, thereby eventually increasing global emissions. Our framework allows to explicitly address this phenomenon.

Taxing energy resource inputs (raw oil and gas) reduces their world price. Countries that do not impose environmental policies gain from the reduced price of g and start producing more energy, mitigating the reduction in the level of the world CO_2 emissions. A tax on the energy sector output τ_i, on the other hand, does not have such distortive effects on the relative price p_g. Moreover, such a tax forces producers of the intermediate and final goods to substitute away from energy as a whole towards other factors of production. This allows countries to achieve a higher reduction in the world level of CO_2 emissions.

Quantitatively, the extent to which countries may affect the world level of carbon emissions depends on the size of the economy and the extent of local resource endowments for two reasons. First, large countries such as the United States have relatively bigger share in world emission of CO_2, hence such countries can considerably reduce the world level of CO_2 by taxing energy production while small countries such as Belgium would have only minor effect. Second, countries with low resource endowment (big importers of energy resources) would induce relatively larger carbon leakage effect by adopting κ_i. Small open economies, have a relatively small impact on the global economy. For example, Australia may reduce emissions by only 0.3 % at the cost of a 10 % reduction in real welfare. On the other hand, large countries may use τ_i to reduce world carbon emissions by a significant amount. For instance, the United States may reduce them by nearly 10 % subject to a 10 % reduction in real welfare. In comparison, a change in the United States' κ_i with the same effect on welfare would reduce global CO_2 emissions by <1 %.

7 Conclusion

We formulate a quantitative general equilibrium model of international trade and energy demand. The model mirrors major stylized facts regarding trade in both intermediate and energy goods, the unequal distribution of energy resource endowments, the centralized market for energy resources, and negative cross-border externalities induced by energy goods production. We propose novel modeling and measurement strategies with regard to the role of energy resource endowments and negative cross-border externalities associated with energy production. We model the latter as a secondary production factor which allows us to give clear-cut predictions on both trade, welfare, and environmental effects in the counterfactual exercises.

We adopt an approach to model counterfactual scenarios which does not require estimating unobservable trade costs or technology parameters. The results for 31 OECD countries and the rest of the world suggest that taxing the use of energy resource inputs is preferable to taxing energy goods output only in the absence of cross-border externalities of energy production. In other words, if a country completely ignores cross-border effects of energy production, a tax on energy resource input (such as raw oil and gas) usage generates lower local CO_2 emissions given the same welfare effects than when taxing local energy production at large. Once cross-border externalities are internalized and countries care about the global level of CO_2 emissions, taxing the domestic energy production becomes preferable to taxing energy resource inputs. The reason is that carbon leakage is significantly lower when taxing energy production than when taxing energy resource inputs. This result is important for policy making because it suggests that taxing energy inputs versus energy producers has quantitatively different effects for welfare and the level of carbon emissions.

Appendix

Measuring Production Shares

Calculating α, β, γ

We can estimate production function parameters of the final good producer by using the first-order conditions from Sect. 2 together with data from OECD's STAN Industry Database. In particular, α can be estimated as the average ratio of total value added in total output according to Eq. (2.12). This ratio is directly observable for 31 OECD countries in the data. We classify the sectors contained in the data into three categories. Intermediate goods are defined as agricultural and manufacturing products, energy is defined as an aggregate of five sectors according to the above classification, and final goods are defined as an aggregate of the following services:

- Community, social, and personal services.
- Construction.
- Finance, insurance, real estate, and business services.
- Transport, storage, and communications.
- Wholesale and retail trade - restaurants and hotels.

To estimate α, we take the ratio of value added to total output for 31 OECD countries in 2000. The average value of α in our sample is 0.54. In order to pin down β and γ, we use STAN input–output tables as follows:

$$\frac{\beta}{\gamma} = \frac{L_i p_{qi} q_{ci}}{L_i p_{ei} e_{ci}} \quad \text{such that} \quad \beta + \gamma = 1 - \hat{\alpha}. \tag{8.1}$$

Notice that $L_i p_{qi} q_{ci}$ is the total value of intermediates used in the production of the final good, and $L_i p_{ei} e_{ci}$ is the total value of energy used.[19] Once we fix α at 0.54, we can solve for β and γ using observations for 31 OECD countries in 2000 as in (8.1). The calculated average values for these two parameters are $\beta = 0.34$ and $\gamma = 0.12$.

Calculating ϵ, ν, and μ

Intermediate tradable goods can be largely classified into two broad classes:

- Agriculture, hunting, forestry, and fishing.
- Manufacturing.

[19] For calculation of the intermediate goods and energy goods intensities of each sector, we exclude the diagonal elements of the input–output matrices.

As in the case of the non-tradable final goods sector, we calculate the average share of value added in total output using STAN input–output tables. The weighted average of ϵ taken across all industries in the two sectors that we classify as tradables and across 31 OECD countries is 0.32 in the year 2000. To calculate ν and μ we pursue the same strategy as in the previous subsection:

$$\frac{\nu}{\mu} = \frac{L_i p_{qi} q_{qi}}{L_i p_{ei} e_{qi}} \quad \text{such that} \quad \nu + \mu = 1 - \hat{\epsilon}. \tag{8.2}$$

This yields $\nu = 0.56$ and $\mu = 0.12$.[20]

Calculating ζ, ξ, χ

Recall the industry classification for the energy sector from above. The weighted average of value added as a share of output in the five energy sub-sectors in our OECD STAN Industry sample is 0.35. We define the energy resource input as*Mining and quarrying (energy)* usage and calculate ξ and χ in the same way as the other production parameters:

$$\frac{\xi}{\chi} = \frac{L_i p_{qi} q_{ei}}{L_i p_g g_{ci}} \quad \text{such that} \quad \xi + \chi = 1 - \hat{\zeta}. \tag{8.3}$$

Solving (8.3) obtains the parameters $\zeta = 0.35$, $\xi = 0.18$ and $\chi = 0.47$.

Border Tax Adjustment

In this section, we provide a brief discussion of how border tax adjustment can be implemented in the vein of the model. Recall that t_{ij} and t_{ij}^e denote import tariffs on intermediate and energy goods, respectively. In terms of the model, there is no difference between border tax adjustment and import tariffs from the point of view of implementing a policy to prevent adverse effects of carbon leakage. For example, Elliott et al. (2010) argue that a border tax adjustment would completely eliminate the problem of carbon leakage. The authors agree that calculating the carbon the content of imported goods could be very costly. Hence, a border tax adjustment is likely to be implemented in the form of a simple import tariff levied on the imports from countries that do not comply with environmental regulations.

In our framework, higher import tariffs will inter alia increase the price of intermediate goods. This, in turn, will increase the price of energy goods, reducing energy demand. On the other hand, in Eaton–Kortum type models there is an optimal level of tariffs. Hence, countries may increase their welfare by generating higher import tariff revenues.[21]. Usually, this two-way link between taxes and energy demand is missing, so that taxes can successfully neutralize carbon leakage without affecting CO_2 emissions directly.

In this experiment, we gradually increase t_{ij} for Australia and the United States such that counterfactual tariffs are $t_{ij}' = \delta t_{ij}$ where t_{ij} is the benchmark tariff and $\delta = (1.00, 1.01, \ldots, 1.50)$. We plot the change in the domestic and world carbon emissions against the change in real welfare in Fig. 5. As in Experiment 1, we use an interval for the value of ω. Notice that a marginal increase in the level of import tariff leads to welfare gains through higher tariff revenues. The same policy, however, leads to an increase in carbon emissions. This is true for both domestic and global CO_2 emissions. Higher import

[20] As an alternative approach, we estimated μ and γ using price data as in (2.13) and (2.4). From that, we obtained $\hat{\mu} \simeq 0.16$ and 0.15. This indicates that the estimated parameters are plausible.

[21] For more details on optimal tariffs for a small open economy see Alvarez and Lucas (2007).

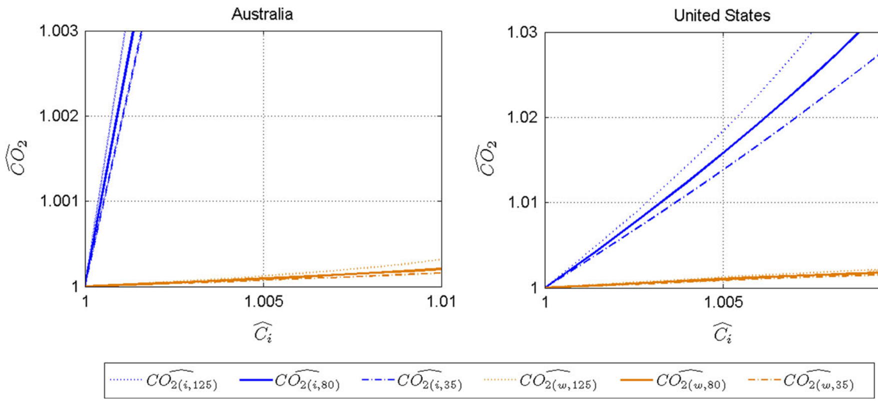

Fig. 5 Effect of t_{ij} on CO_2 emissions and welfare

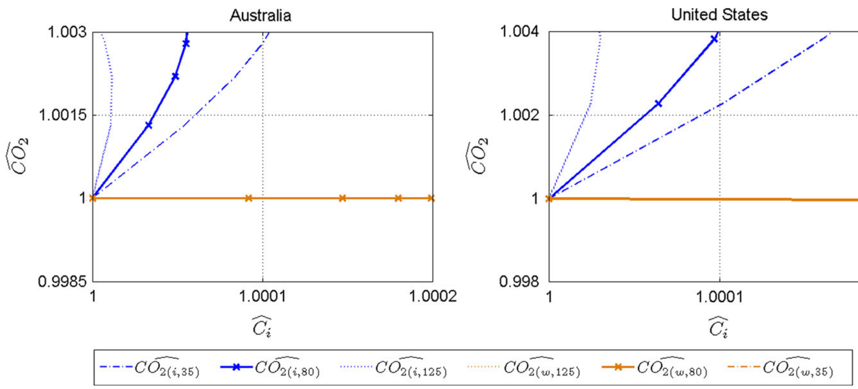

Fig. 6 Effect of t_{ij}^e on CO_2 emissions and welfare

tariffs increase the price of intermediate goods. As a consequence, producers substitute away from intermediate goods towards energy goods, thereby increasing domestic energy demand. The latter is translated into higher world energy demand and hence more global CO_2 emissions.

Alternatively, consider a counterfactual exercise about energy goods tariffs with $(t_{ij}^e)' = \delta t_{ij}^e$ where t_{ij}^e is the benchmark tariff and $\delta = (1.00, 1.01, \ldots, 1.50)$ (Fig. 6).

Trade in energy is very limited to start with. The average of π_{ii}^e in our sample is 0.96. Hence, an average country in our sample imports only 4 % of energy goods. Our conjecture is that unobservable trade costs are too high for more intense trade in energy goods. This low trade intensity effectively means that both small and large countries experience similar welfare and environmental effects as import tariffs on energy goods are changed. The imposition of higher energy import tariffs increases domestic CO_2 emissions. At first glance, this may seem counterintuitive as higher energy import tariffs must increase domestic energy prices and reduce energy demand. Yet, while it is correct that the domestic price of energy p_{ei} rises with t_{ij}^e, higher energy tariffs and subsequently higher energy goods prices also increase the price of intermediate goods. The substitution effect towards energy is stronger because intermediate goods have higher production weights compared to energy. Hence, we actually observe an increase in domestic energy demand as a result. This change, however, is small and does not affect world emissions of CO_2 significantly.

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