A Regional Trade Model with Ricardian Productivity Gains and Multi-technology Electricity Supply

Frank Pothen* and Michael Hübler†

Hannover Economic Papers (HEP) No. 585

ISSN 0949-9962

March 10, 2017

Abstract

This article presents an applied general equilibrium model which combines the theoretical foundations of an Eaton-Kortum type model of international trade with the complexity of a global multi-region, multi-sector Computable General Equilibrium (CGE) model of production and consumption. The Eaton-Kortum model features endogenous trade-induced productivity gains via Ricardian specialization and takes non-tariff trade costs into account. Model regions and sectors can be disaggregated, e.g., representing technology-specific electricity generation. The models is tailored to explicitly study the German Federal State of Lower Saxony, a prime location for renewable electricity generation in Germany with ambitious climate policy goals. The calibration utilizes the structural estimation of a gravity model with constraints, while the disaggregation adapts methods used in regional science and energy economics. With these features the model goes beyond standard CGE models and provides new insights in the nexus between trade policy and climate policy. Simulations suggest that the removal of tariffs creates smaller welfare gains than a comparable reduction of non-tariff barriers to trade but also a slightly smaller increase in global CO_2 emissions. Trade policy-induced productivity gains and renewable energy subsidies significantly reduce carbon leakage from the EU to the rest of the world by making the EU more CO_2-efficient. With its large wind power potential, Lower Saxony is less susceptible to negative effects of climate policy than the rest of Germany.

JEL Classifications: C68; F10; F18; Q40

Keywords: international trade; regional model; climate policy; renewable energy; CGE

*Corresponding main author, email: pothen@iuw.uni-hannover.de, tel: +49-511-762-14575, fax: +49-511-762-2667, Leibniz Universität Hannover, Institute for Environmental Economics and World Trade, Königsworther Platz 1, 30167 Hannover, Germany.

†Leibniz Universität Hannover, Institute for Environmental Economics and World Trade.

1 Introduction

The 2015 United Nations Climate Change Conference in Paris was an important step towards a climate policy solution with global coverage. In an increasingly internationalized world economy, *global* coverage of climate policy appears to be inevitable in order to achieve ambitious climate policy goals. The share of merchandise trade in GDP, for instance, rose from 17.5% in 1960 to 50% in 2014 (World Bank, 2016).

Unilateral actions are, nevertheless, dominating international climate policy. They are not only implemented by nations or the European Union, but also by sub-national bodies. The German Federal State of Lower Saxony, for instance, investigates whether it will by able to satisfy its energy demand completely from renewable sources by 2050 (NMUEK, 2016). These regional climate policy initiatives are not only highly intertwined with global climate policy but also interact with trade policy. Trade-induced sectoral specialisation or productivity gains might affect sub-national regions like Lower Lower Saxony differently than the country as a whole, increasing or decreasing costs of their climate policy.

Trade policy and climate policy can affect each other in various ways. On the one hand, a reduction of trade barriers enlarges trade volumes and production, which is likely to increase CO_2 emissions and carbon leakage[1] (Frankel and Rose, 2005; Peters and Hertwich, 2008; Böhringer et al., 2012), whereas increased specialization can in- or decrease emissions and leakage via structural change across sectors and productivity gains within sectors. On the other hand, carbon pricing and renewable energy support affect trade and specialization. The implications for productivity as well as carbon leakage are unclear ex ante. The interactions between these two policies have hardly been considered by scholars and policy makers so far. Hence, this article sheds light on relevant interactions.

This article introduces a novel general equilibrium model which is tailored to study these interactions between climate and trade policy. By revealing the underlying economic mechanisms, it provides qualitative and quantitative inference on how these policy fields affect each other. The model combines the trade-theoretic foundations of the Eaton and Kortum (2002) model,[2] including endogenous Ricardian specialization and productivity gains, with the flexibility and expandability of a Computable General Equilibrium (CGE) model (e.g. Böhringer and Löschel, 2006; Chen et al., 2015).

In the Eaton and Kortum (2002) model, sectors produce a continuum of differentiated

[1] The increase in CO_2 emissions in other regions due to the introduction of a CO_2 price in one region.

[2] The seminal general equilibrium model by Eaton and Kortum (2002) explains international trade flows via a combination of technology differentials, relative input costs and iceberg trade costs.

varieties of their goods. Neither firms nor consumers have preferences over an individual variety from specific regions. They purchase a variety from the region offering it for the least price. This assumption is particularly plausible for relatively homogeneous energy and resource-intensive upstream goods. Hence, the Eaton and Kortum (2002) model is an appealing alternative to the Armington (1969) model for studying energy and climate policies.

The trade model is calibrated by using a structural estimation approach (drawing on Balistreri and Hillberry, 2007; Balistreri et al., 2011), in which the market clearing conditions of the model enter a gravity model estimation as side constraints. Unlike unconstrained gravity models, this approach ensures that the baseline constitutes a general equilibrium of the model.

Our model allows for a technology-specific representation of the electricity sector (Böhringer, 1998; Böhringer and Löschel, 2006). Renewable electricity generation can react endogenously to trade and climate policy, taking into consideration regional differences in the potential for expanding renewable power generation. A constrained optimization technique following Sue Wing (2008) is implemented to disaggregate the electricity sector.

The overwhelming majority of general equilibrium models represents nations or group of nations (for an exception see Bosello and Standardi, 2015). To study climate policy in Lower Saxony, we disaggregate Germany into two regions: Lower Saxony and the Rest of Germany. Taking Lower Saxony as example, the model is not only able to investigate climate policies by sub-national regions but also to study differences in how international trade and climate policy affects regions within a country. The disaggregation utilizes a regional science approach (based on Kronenberg, 2009; Többen and Kronenberg, 2014).

The application of the model to the European Union (EU) is particularly interesting because of the EU's regional heterogeneity as well as the implementation of climate and energy policies at different political levels (EU, national states, federal states etc.). The European Union Emissions Trading System (EU ETS) is Europe's key climate policy instrument (Ellerman et al., 2010) covering around 11,000 installations and 45% of the EU's CO_2 emissions. Within the EU, we focus on Germany because it is a front-runner in the transition towards a low-carbon economy and has heavily subsidized renewable energy. Within Germany, the federal state of Lower Saxony is the prime location for installing wind power plants, while its population density is lower than and the sectoral composition is different from the German average. Lower Saxony's shares of agriculture and food production in total production, for example, are relatively high but there is no coal extraction.

We implement two sets of policy scenarios which highlight the interaction between climate and trade policy. In the global trade policy scenarios, we remove either tariffs and trade subsidies or we reduce non-tariff barriers to an equivalent extent. In both trade policy scenarios, we find the following results. The share of renewables in the electricity sectors of Lower Saxony and the rest of Germany increases by about 16% because lower trade costs enhance output and thus carbon emissions. The allowances price in the EU ETS rises in response to increasing output, creating a price signal that shifts power generation towards renewables. Due to its large wind power potential and the corresponding low abatement costs, Lower Saxony's resulting emissions reduction of over 16% is twice the reduction in the rest of Germany. While the estimated trade policy-induced welfare gains stay below 1%, the reduction of non-tariff barriers creates larger gains than the removal of subsidies and tariffs in all model regions including Lower Saxony and the rest of German.

In South Korea, on the contrary, trade-induced specialization shifts production towards energy-intensive sectors so that CO_2 emissions rise by one third. When removing tariffs, the former Soviet Union region experiences a 20% increase in total factor productivity. Notwithstanding, as a major fossil energy exporter, it experiences a 2% welfare drop because it refrains from exerting power on fossil fuel markets. This loss turns into an 8% welfare gain when removing non-tariff barriers which constitute a mere inefficiency without tax revenues.

With reduced non-tariff barriers, the EU climate policy is also responsible for less carbon leakage to the rest of the world, because the reduction of non-tariff barriers supports structural change towards less energy-intensive industries and thus eases decarbonization within the EU. On the opposite, driven by policy-induced structural change, total factor productivity becomes slightly lower and global emissions slightly higher when non-tariff barriers are reduced than when tariffs are removed.

In the EU climate policy scenarios, we first tighten the emissions cap by 13% relative to 2011 which corresponds to the reduction scheduled for 2020. Then, we add subsidies for wind and solar power as in practice in Germany. Faced with higher input costs due to the tighter emissions cap, Germany specializes in goods and varieties of goods which it can produce efficiently. Thereby, climate policy induces productivity gains for Germany. In the other model regions, on the contrary, the induced productivity effects are negative.

Lower Saxony experiences a welfare drop of 0.14% due to the more restrictive climate policy target. Welfare falls twice as much in the rest of Germany. With its large potential for renewable energy generation, in particular wind power, and its sectoral structure exhibiting higher agricultural and smaller manufacturing shares, Lower Saxony is less susceptible to negative effects of climate policy. The application of renewable energy subsidies reduces carbon leakage and global emissions and creates minor welfare gains, especially for Germany and Italy.

Because of its strong link between theory and empirics, the Eaton and Kortum (2002) model has been frequently extended and applied (Eaton and Kortum, 2012). Applications range from theory-consistent measurement of competitiveness (Costinot et al., 2011), the determinants of productivity (Levchenko and Zhang, 2016) and impacts of expanding transport infrastructure (Donaldson, 2010) to the welfare effects of international trade agreements (Caliendo and Parro, 2015). Our model setup draws on the work by Eaton and Kortum (2002), Alvarez and Lucas (2007), Caliendo et al. (2014) and Caliendo and Parro (2015).

So far Eaton and Kortum (2002) type models have hardly been used to study climate change-related issues. A notable exception is the work by Costinot et al. (2016) who investigate how climate change alters comparative advantages in agriculture and how this, in turn, affects GDP. Our article describes, to our knowledge, the first climate or energy policy application. Furthermore, besides a subnational representation of the United States in the study by Caliendo et al. (2014), Eaton and Kortum type models have, to our knowledge, not been calibrated to regionally or technologically disaggregated data.

Models based on Eaton and Kortum (2002) usually assume Cobb-Douglas production functions.[3] These imply that all intermediate inputs can be substituted with each other in the same manner and that the elasticity of substitution between them equals unity. This simplification is problematic when studying climate and energy policies, because the substitutability of energy carriers among each other or with value added is heterogeneous and crucial for the magnitude of policy effects. Therefore, we add to the Eaton and Kortum literature by implementing nested Constant Elasticity of Substitution (CES) production and consumption functions (following van der Werf, 2008), which are common in the CGE policy modeling literature (e.g. Böhringer and Löschel, 2006; Chen et al., 2015) and which allow the substitutability to vary between inputs. As usual in this literature, our main data source is the Global Trade Analysis Project (GTAP) database.

[3]Caliendo et al. (2014) present a variant of their model with Constant Elasticity of Substitution production functions. It is, to our knowledge, the only study which employs CES production functions in the Eaton and Kortum (2002) literature.

The article proceeds as follows. Section 2 presents the theoretical model. Section 3 describes the structural estimation and disaggregation procedure. Section 4 defines the policy scenarios and interprets the simulation results. Section 5 concludes with policy implications and a discussion.

2 Model

In the course of this section, the model is set up and solved.

2.1 Overview

We begin with a narrative and a technical overview of the model structure.

2.1.1 Summary

The model presented in this study is a static Ricardian general equilibrium model based on Eaton and Kortum (2002) as well as Caliendo et al. (2014) and Caliendo and Parro (2015). There is one representative consumer per region (subsection 2.2). A representative firm per sector and region produces a continuum of differentiated varieties of the sector's good (subsection 2.3). Individual varieties from different regions are perfect substitutes. The steel sector in the USA, for instance, produces a large number of steel varieties (which are termed grades in steelmaking). But if an individual variety is selected, it is irrelevant if it was produced in the United States or in China because it serves the same purpose in production. Likewise, the representative consumer of each region has no preferences over varieties from different countries.

The varieties are combined via a CES function to produce the sector's output (subsection 2.3). The pattern of international trade depends on sector-specific absolute productivities, variety-specific probabilistic productivities, and trade costs (subsection 2.4). Based on these productivities, Ricardian specialization in varieties creates endogenous (productivity) gains from trade. This is an important advancement compared to the familiar Armington (1969) type model of trade which is commonly used in Computable General Equilibrium (CGE) models. In Armington models, gains from trade via Ricardian specialization are determined by the benchmark data and do not adjust endogenously in counterfactuals. We assume constant returns to scale and perfect competition in all markets. Hence, firms do not earn profits.

The model allows for regional disaggregation below the national level (for the calibration see section 3). It allows for sectoral disaggregation as well. The electricity sector is disaggregated in various emitting and non-emitting generation technologies (subsection 2.3.2). As a consequence, climate and energy policy does not only affect energy use in production and consumption but also the decarbonization of electricity supply.

Three primary production factors are considered in the model: labor, capital, and natural resources. Labor and capital can move freely across sectors but are internationally immobile. Natural resources are specific to the corresponding extractive industries such as crude oil production or mining. Under climate policy with carbon pricing, fossil fuel inputs require corresponding inputs of emissions allowances.

2.1.2 Structure

The model differentiates between sectors indexed i or j as well as regions indexed r, s or rr. The index r usually represents the producing or exporting region while s represents the consuming or importing region. Regions can be individual countries, groups of countries, or German Federal States. The indices i and j encompass all industries of the economy including the sectors electricity, transportation and services. All variables and parameters, which concern individual varieties, are written in lower-case latin letters. Lower case greek letters denote relative values such as tax rates or input shares. Variables and parameters of sectors are denoted in upper-case letters.

An equilibrium of the model is reached if a set of 13 equilibrium conditions are simultaneously fulfilled.[4] Table 1 lists the equilibrium conditions and the corresponding equation numbers as well as the associated endogenous variables, their symbols and dimensions (see subsection 2.5 for market clearing conditions in individual markets).[5]

The model setup encompasses five types of equilibrium conditions. The income balance condition, zero-profit conditions and market clearing conditions are standard elements of CGE models written as a Mixed Complementarity Problem (MCP). The Eaton and Kortum (2002) type trade model contributes additional equations which determine goods' prices and trade shares. If climate policy with the possibility to allocate allowances for free is taken into account, a corresponding market clearing condition for emissions allowances and a policy condition which represents the free allocation of allowances will be required.

The model is implemented as a Mixed Complementarity Problem in GAMS (General Algebraic Modeling System; Bussieck and Meeraus, 2004) and solved by using the PATH

[4]See Alvarez and Lucas (2007) for a proof of the existence and the uniqueness of an equilibrium in the Eaton and Kortum (2002) model.

[5]Theses variables are directly determined by the model solution; further variables are derived from them.

algorithm (Dirkse and Ferris, 1995). Demand and per-unit cost functions are formulated in the calibrated share form (Böhringer et al., 2003) which normalizes the baseline variables to unity to ease the model solution and interpretation.

Table 1
Equilibrium conditions and variables

Variable	Equation		Symbol	Dimension
Income balance condition:				
Consumer income	**MQ (1)**	(2)	Y_r	R
Zero-profit conditions:				
Intern. transport services	**MQ (2)**	(6)	X_h^T	H
Per-unit input costs	**MQ (4)**	(8)	$c_{i,r}$	$I \times R$
Sectoral goods price index	**MQ (5)**	(9)	$P_{i,r}$	$I \times R$
Trade flows:				
Bilateral trade shares	**MQ (6)**	(11)	$\pi_{i,r,s}$	$I \times R \times R$
Market clearing conditions:				
Prices of intern. transp. serv.	**MQ (3)**	(16)	P_h^T	H
Factor prices	**MQ (7)**	(13)	$P_{f,r}^F$	$F \times R$
Resource prices	**MQ (8)**	(14)	$P_{i,r}^{RES}$	$I \times R$
Prices of the fixed factors	**MQ (9)**	(15)	$P_{g,r}^{FFEG}$	$G \times R$
Output of goods/sectors	**MQ (10)**	(19)	$X_{i,r}$	$I \times R$
Total Demand	**MQ (11)**	(18)	$D_{i,r}$	$I \times R$
Emissions price	**MQ (12)**	(20)	P^{ETS}	1
Policy condition:				
Subsidy for free allowances	**MQ (13)**	(21)	$\phi_{i,r}^{ETS}$	$I \times R$

r/s = region, i = sector, h = transport service sector, f = factor, g = electricity generation technology, R = number of regions, I = number of sectors, H = number of transport service sectors, F = number of factors, G = number of technologies, ETS = emissions trading scheme, MQ = model equation.

2.2 Consumption

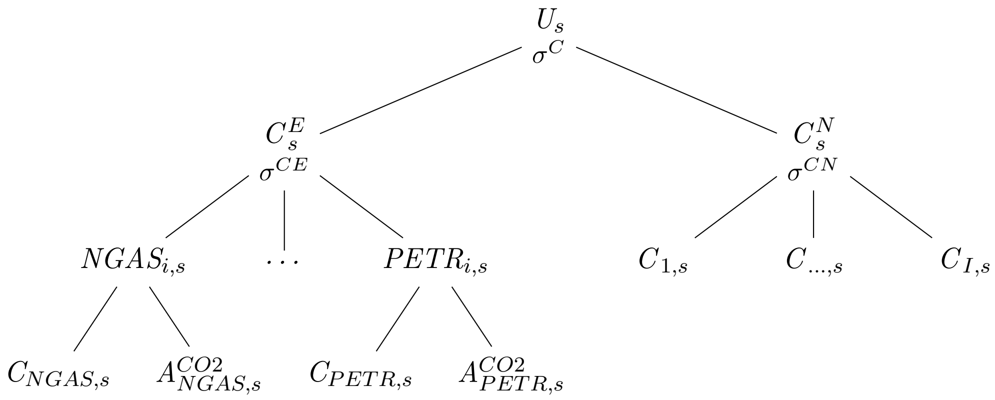
In each region, a representative consumer s chooses the optimal bundle of goods $C_{i,s}$ from sectors i which maximizes her utility U_s. $P_{i,s}$ denotes the price of good i in s. $\tau_{i,s}^c$ is an ad-valorem consumption tax rate. We assume that the representative consumer spends a fixed fraction ξ_s of her income Y_s on consumption. The remainder is invested.

$$\max_{C_{i,s}} U_s = U_s\left(C_{1,s}, C_{2,s}, \dots\right) \text{ subject to} \tag{1}$$

$$\xi_s Y_s = \sum_i P_{i,s} C_{i,s}(1 + \tau_{i,s}^c)$$

Consumers have nested CES preferences over sectors' goods. In the nested CES function depicted by figure 1 goods are combined step-wise to allow for differentiated degrees of substitutability between them. A higher elasticity of substitution σ implies better substitutability.

Figure 1
Nesting structure of the consumer's utility function



The representative consumer in s combines energy goods into an energy aggregate C_s^E. It comprises the consumption of coal ($COAL_s$), crude oil ($CRUD_s$), gas ($NGAS_s$), refined petroleum ($PETR_s$), and electricity ($ELEC_s$). The elasticity of substitution between energy goods is denoted σ^{CE}.

Consumers emit carbon dioxide when they burn fossil fuels. To reflect these emissions, the consumption of fossil fuels $C_{i,s}$ $\forall i \in \{COAL, CRUD, NGAS, PETR, ELEC\}$ is connected with CO_2 $A^{CO2}_{i,s}$. The nest of natural gas inputs $NGAS_s$, for instance, consists of purchases from the natural gas sector $C_{NGAS,s}$ and the corresponding emissions $A^{CO2}_{NGAS,s}$. Fossil fuels and emissions are combined in fixed proportions via Leontief functions because the carbon content of each good is physically determined.

The other goods are combined into a non-energy aggregate C_s^N with an elasticity of substitution σ^{CN}. Energy and non-energy aggregates are subsequently aggregated to total consumption. The elasticity of substitution between them is σ^C.

The representative consumer is endowed with exogenous region-specific quantities of the factors labor, capital, natural resources and fixed factors for electricity generation (see figure 3 below). She supplies them inelastically on factor markets and receives factor income. She, furthermore, receives income from net taxes and selling emissions allowances. The representative consumer's current account deficit or surplus is held constant.

Equation (2) is a stylized version of the **income equation** representing **model equation MQ (1)**, in which $P^F_{f,s}$ indicates a factor price and $\tilde{N}_{f,s}$ the exogenous endowment with factor f in region s. Θ_s symbolizes the endogenous sum of net tax revenues (tax revenues minus subsidy payments) and Δ_s the exogenous current account deficit of s.

$$Y_s = \sum_f P^F_{f,s} \tilde{N}_{f,s} + \Theta_s + \Delta_s \tag{2}$$

We define real consumption $\frac{\xi_s Y_s}{c^C_s}$ as the welfare measure for policy analyses where c^C_s denotes the true-cost-of-living index, the price index of the optimal consumption bundle implied by the CES utility function depicted in figure 1.

2.3 Production

The production side features varieties of each good, CES functions and technologies.

2.3.1 Varieties

In each sector i, a representative firm produces a continuum of differentiated varieties of the sector's good. Constant returns to scale and perfect competition imply that firms earn no profits and the number of firms in equilibrium is neither determined nor important.

The representative firm combines primary factors and intermediate inputs according to a CES nest structure as explained in the next subsection (see figures 2 and 3). Equation (3) defines the production function of variety $z_{i,r}$. $q_{i,r}(z_{i,r})$ denotes the output and $q^{CES}_{i,r}$ the cost-minimizing input bundle derived from the CES technology.

$$q_{i,r}(z_{i,r}) = z_{i,r} T_{i,r} q^{CES}_{i,r} \tag{3}$$

Two parameters determine the efficiency of producing the variety $z_{i,r}$. $T_{i,r}$ represents the absolute productivity of transforming the input bundle into the output $q_{i,r}(z_{i,r})$. $T_{i,r}$ is exogenous and deterministic; it varies across sectors and regions but is the same for all varieties of one good.

$z_{i,r}$ is a probabilistic, variety-specific productivity. $z_{i,r}$ unequivocally corresponds to a specific variety. Therefore, we use $z_{i,r}$ to index individual varieties. $z_{i,r}$ is drawn from a Fréchet distribution with the cumulative distribution function $\Omega_{i,r}(z_{i,r}) = e^{-z_{i,r}^{-\theta_i}}$. θ_i is the shape parameter of the Fréchet distribution; it determines the variation between productivity draws. The higher θ_i, the closer the productivity draws. The Fréchet distribution of productivities can be derived from a process of innovation and diffusion (Kortum, 1997; Eaton and Kortum, 1999).

The representative firm combines varieties with a Dixit-Stiglitz technology (4) to produce the sectoral output $Q_{i,r}$. σ is the elasticity of substitution between varieties.

$$Q_{i,r} = \left[\int q_{i,r}(z_i)^{\frac{\sigma-1}{\sigma}} \omega_i(z_i) \, \mathrm{d}z_i \right]^{\frac{\sigma}{\sigma-1}} \tag{4}$$

2.3.2 Technologies

Most models based upon Eaton and Kortum (2002) assume Cobb-Douglas production functions.[6] We implement a nested CES production structure which allows for different degrees of substitutability between fossil fuels and other inputs.

Figure 2
Nesting structure of all sectors except electricity

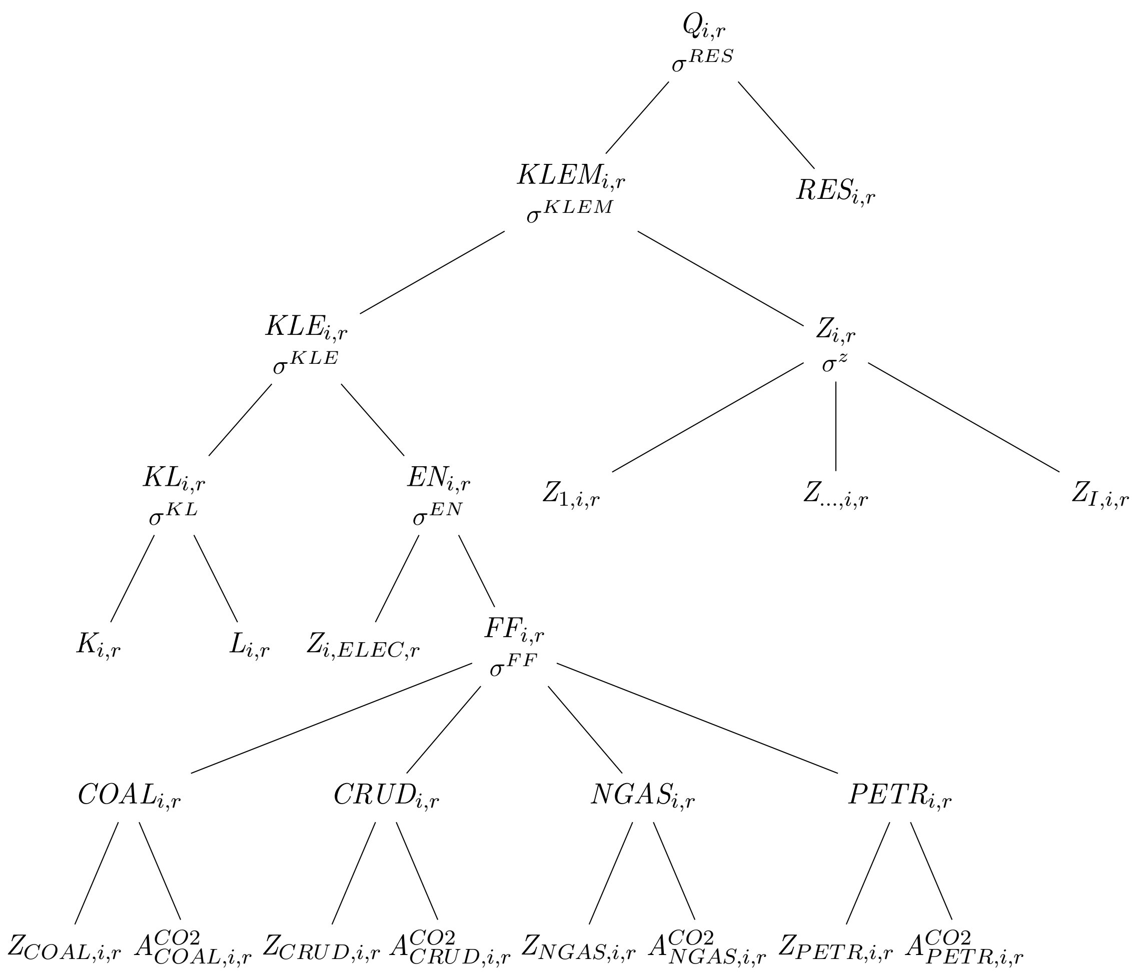


Figure 2 depicts the nesting of all goods i except the electricity sector. It shows how primary factors and intermediate inputs $Z_{j,i,r}$ are combined to produce a quantity $Q_{i,r}$. Let's take the capital-and-labor nest $KL_{i,r}$ as an example for the interpretation of figure 2. Sector i in r combines inputs of capital $K_{i,r}$ and labor $L_{i,r}$. σ^{KL} represents the elasticity

[6] Intermediate inputs are aggregated by using a Cobb-Douglas technology, so are primary factors. The intermediate aggregate and value added are combined by another Cobb-Douglas function.

of substitution between these inputs. A higher elasticity of substitution implies better substitutability, and a larger input share a higher importance of the corresponding factor for production.

The fossil fuels nest combines inputs of coal ($COAL_{i,r}$), natural gas ($NGAS_{i,r}$), refined petroleum ($PETR_{i,r}$), and crude oil ($CRUD_{i,r}$). The elasticity of substitution between fossil fuels is denoted σ^{FF}. Each fossil fuel nest is a combination between the intermediate input of the corresponding sector, $Z_{j,i,r}$, and CO_2 emissions from burning them, $A^{CO2}_{j,i,r}$. They are combined by using a Leontief production function.

In the energy nest $EN_{i,r}$, the fossil fuel aggregate is combined with the input of electricity $Z_{i,ELEC,r}$. This reflects that electricity drives electric machines and generates light, while fossil fuels drive combustion engines and generate heat. The capital and labor aggregate $KL_{i,r}$ and the energy aggregate are combined in the $KLE_{i,r}$ nest with an elasticity of substitution of σ^{KLE}. A production structure, in which value added can be substituted for energy, has proven to be empirically convincing (van der Werf, 2008).

The $KLE_{i,r}$ nest is combined with intermediate inputs of non-energy goods. The non-energy intermediate nest $Z_{i,r}$ aggregates intermediate inputs $Z_{j,i,r}$ $\forall j \neq \{COAL, NGAS, PETR, CRUD, ELEC\}$ with the elasticity of substitution σ^{z}.

Resource-extracting sectors (coal, crude oil, natural gas, and other mining) use an additional primary factor of production, a sector-specific natural resource $RES_{i,r}$, which is combined with the $KLEM_{i,r}$ nest to produce output $Q_{i,r}$.

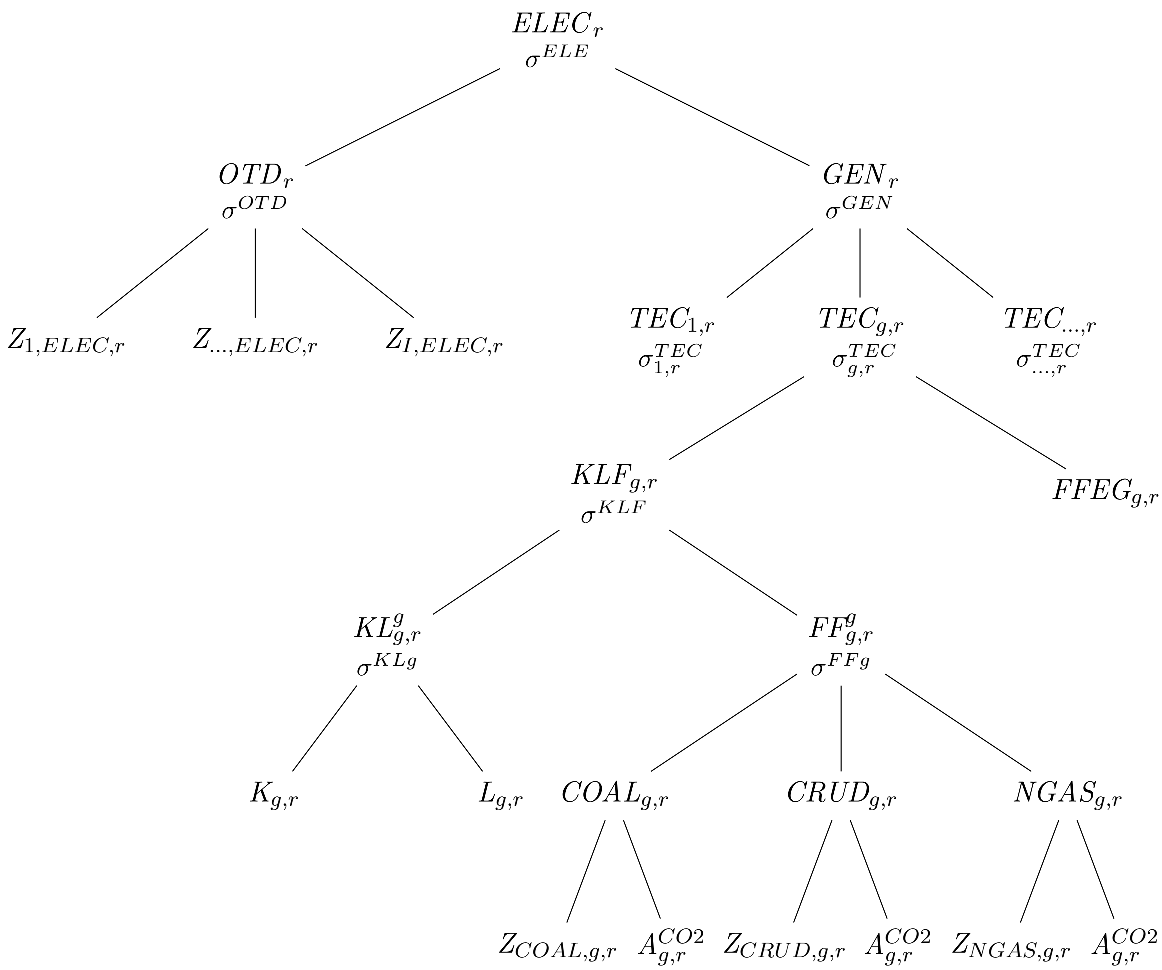
Some CGE models studying climate and energy policy represent the electricity sector in a detailed way (Böhringer, 1998; Paltsev et al., 2005; Böhringer and Löschel, 2006; Sue Wing, 2008; Cai and Arora, 2015). We follow this literature by defining the electricity sector as illustrated by figure 3.

We distinguish between two activities in the electricity sector. The overhead, distribution, and transmission activity OTD_r represents the grid as well as services provided by the sector. Following Sue Wing (2008), we assume that the OTD activity uses all intermediate inputs except coal, natural gas, and crude oil but no capital or labor. The elasticity of substitution between inputs in the OTD activity is denoted σ^{OTD}.

The generation activity GEN_r represents generation of electricity itself. It aggregates the inputs by individual generation technologies $TEC_{g,r}$, where g indexes the technology. Table 2 displays all generation technologies represented by the model. The third column in table 2 indicates whether the technology uses fossil fuels.

Capital and labor are combined in the $KL^{g}_{g,r}$ nest. The corresponding elasticity of

Figure 3
Nesting structure of the electricity sector



substitution is σ^{KLg}. The inputs of coal, natural gas, and crude oil are combined within the $FF^g_{g,r}$ nest. They include the inputs of the fossil fuels, $Z_{j,g,r}$, as well as the corresponding CO_2 emissions, $A^{CO2}_{j,g,r}$. Following Paltsev et al. (2005), we assume that refined petroleum is not used to generate electricity. The capital-labor aggregate and the fossil fuels are combined in the $KLF_{g,r}$ nest.

Usually, a technology does not employ more than one fossil fuel. Coal-fired power plants use coal, gas-fired plants natural gas. In regions, for which we do not disaggregate the generation technologies, we use an aggregate technology which uses coal, gas, and crude oil ($gAGG$). In this case, we assume an elasticity of substitution σ^{FFg} between fossil fuels.

Capital, labor and fuels are combined with a fixed factor in electricity generation ($FFEG_{g,r}$) in the $TEC_{g,r}$ nest. It represents barriers to the expansion of individual technologies. The interpretation of the fixed factor differs by technology. For wind power,

Table 2
Power generation technologies

g	Description	Fossil
$gCOA$	Coal-fired plants	Yes
$gOIL$	Oil-fired plants	Yes
$gGAS$	Gas-fired plants	Yes
$gNUK$	Nuclear fission	No
$gHYD$	Hydroelectric plants	No
$gWND$	Onshore and offshore wind	No
$gSOL$	Photovoltaics and thermo-solar plant	No
$gGET$	Geothermal and wave sources	No
$gBIO$	Biomass and waste	No
$gAGG$	Aggregate in r without technology-specific generation	Yes

for instance, it represents the limited availability of suitable sites for wind turbines. For nuclear power plants and, to a lesser degree, other conventional technologies, the fixed factor represents political restrictions to an expansion of production.

Note that the elasticity of substitution between $KLF_{g,r}$ and $FFEG_{g,r}$, $\sigma_{g,r}^{TEC}$, can differ by technology g and region r. This allows, for instance, to assume stronger political constraints for building new nuclear power plants than for building new coal-fired plants. Furthermore, regional differences in potentials for renewable energy can be accounted for.

2.4 Trade

Drawing upon the varieties and technologies defined in the previous subsection, this subsection sets up the Eaton and Kortum (2002) type trade model. It starts by defining trade costs and proceeds by deriving price indices and trade shares.

2.4.1 Costs

Determining price differentials between regions, trade costs are a crucial part of the model. Multiplicative trade costs $\delta_{i,r,s}$ are associated with the flow of good i from region r to region s. Unlike in the Melitz (2003) model, there are no fixed costs of exporting. Thus, international trade does not generate (additional) economies of scale and profits. Trade within a region is assumed to be costless ($\delta_{i,s,s} = 1$).

The functional form of the overall trade costs $\delta_{i,r,s}$ is defined by equation (5). We differentiate between four components of trade costs: First, import tariffs $\tau_{i,r,s}^{m}$. Second, transport margins $\psi_{h,i,r,s} \cdot P_h^T$. Third, export subsidies $\tau_{i,r,s}^{e}$. Fourth, iceberg trade costs

$\tilde{\delta}_{i,r,s}$. The components are multiplied by each other because they affect price differentials simultaneously and interactively.

$$\delta_{i,r,s} = (1 + \tau^m_{i,r,s})(1 + \sum_h \psi_{h,i,r,s} P^T_h)(1 - \tau^e_{i,r,s})\tilde{\delta}_{i,r,s} \tag{5}$$

$\tau^m_{i,r,s}$ denotes the ad-valorem tariff (rate) imposed on imports of i from region r to region s. Likewise, $\tau^e_{i,r,s}$ stands for an ad-valorem subsidy (rate) for exports of i from r to s. The former is collected by region s, the latter is paid by region r. (Export subsidies can also be negative and thus equivalent to export taxes.) Both $\tau^m_{i,r,s}$ and $\tau^e_{i,r,s}$ are exogenous.

$\tilde{\delta}_{i,r,s}$ is interpreted as iceberg trade costs. They represent costs other than tariffs and transportation costs which firms incur when they export their products. They include transaction costs due to differences in language and regulation or other non-tariff barriers to trade. The intuition for iceberg costs is that part of a good "melts away" when it is shipped abroad. Iceberg costs imply that the transaction costs involve the same input bundle and production technology as the traded good.

$\psi_{h,i,r,s}$ is the international transport margin. For each unit of good i shipped from region r to region s, $\psi_{h,i,r,s}$ units of international transport services provided by sector $h \in i$ are needed. h indexes the transport sectors. The model considers one transport sector ($TRNS$) but the underlying data allows to distinguish between up to three transport sectors: air transport, water transport, and other transport. The explicit representation of international transport services isolates how the demand for transport services reacts to policy changes or exogenous shocks.

$\psi_{h,i,r,s}$ is multiplied by the price of international transport services P^T_h. If the price of international transport services falls, for instance due to technological improvements, the trade costs $\delta_{i,r,s}$ fall as well. While $\psi_{h,i,r,s}$ is exogenous, P^T_h is endogenous in the model.

International transport services are provided by a global transport sector. Using a Cobb-Douglas technology, the production function of this sector combines inputs from transport sectors h of all regions r.[7]

The following **zero-profit condition** (6) applies to the global transport sector and represents **MQ (2)**. It determines the output of international transport services, F_h. Output is chosen such that the price for the international transport services P^T_h equals the per-unit input costs $\prod_r \left(\frac{P_{h,r}}{\zeta_{h,r}}\right)^{\zeta_{h,r}}$ implied by the Cobb-Douglas production function.

[7] It is not observable in the data which regions provide the international transport services to ship a good, for instance, from China to the United States. Assuming international transport services to be a global aggregate is a common solution to cope with this lack of data.

$\zeta_{h,r}$ is the exogenous input share of region r in international transport services.

$$P_{h,r}^{T} - \prod_{r} \left(\frac{P_{h,r}}{\zeta_{h,r}} \right)^{\zeta_{h,r}} = 0 \tag{6}$$

2.4.2 Prices

In this subsection, we exploit the properties of the Fréchet distribution and the previous assumptions to derive a simple expression for the sectoral prices $P_{i,s}$. We draw upon Caliendo et al. (2014) who detail a simpler yet similar model. Let $c_{i,r}$ denote the per per-unit input costs of sector i in r and $\tau_{i,r}^{x}$ an output tax. Then, under perfect competition, the price $p_{i,r,s}(z_{i,r})$ of variety $z_{i,r}$ in region s equals:

$$p_{i,r,s}(z_{i,r}) = \frac{c_{i,r}\delta_{i,r,s}}{z_{i,r}T_{i,r}(1-\tau_{i,r}^{x})} \tag{7}$$

With productivity varying between varieties, endogenous (Ricardian) productivity gains from trade via specialization arise. Imagine, for example, a counterfactual scenario in which European steel producers face fiercer competition from China, because the Chinese steel sector experiences a positive productivity shock. As a consequence, Europe imports more of the cheap Chinese varieties and shifts production to steel varieties, for which it has the highest productivity $z_{i,r}$. Thus, the increased competitive pressure from abroad (China) induces a productivity gain at home (Europe).

Let $c_{i,r}$ denote the per per-unit input costs of sector i in r. Equation 8 below is a stylized formulation of the per-unit input costs of producers in non-electricity sectors. It constitutes the fourth model equation **MQ (4)**. $c_{i,r}^{x}$ represents the per-unit input costs of nest x in sector i in r. The nesting structure is displayed in figure 2. The dots represent the corresponding prices including taxes of intermediate inputs and primary factor inputs.

$$c_{i,r} = c_{i,r}^{KLEM}\left[c_{i,r}^{KLE}\left[c_{i,r}^{KL}\left[\ldots\right], c_{i,r}^{E}\left[\ldots, c_{i,r}^{FF}\left[\ldots\right]\right]\right], c_{i,r}^{Z}\left[\ldots\right]\right] \tag{8}$$

It can be shown that the sectoral price $P_{i,s}$ can be written as in equation (9); see appendix C as well as Caliendo et al. (2014) for details. Equation (9) is denoted **MQ (5)** which together with MQ (4), determines the sectoral prices in the model. γ_i is a constant.

$$P_{i,s} = \gamma_i \left[\sum_{r} T_{i,r}^{\theta_i} (1-\tau_{i,r}^{x})^{\theta_i} (c_{i,r}\delta_{i,r,s})^{-\theta_i} \right]^{-\frac{1}{\theta_i}} \tag{9}$$

A region s is in autarky if the trade costs equal infinity, $\delta_{i,r,s} = \infty \ \forall \ r \neq s$. In this case, the price only depends on the productivity, per-unit input costs, and taxes in s. If s can trade with other regions r, their productivities $T_{i,r}$, per-unit input costs $c_{i,r}$, and taxes $\tau^x_{i,r}$ as well as the bilateral trade costs $\delta_{i,r,s}$ influence the price in s.

High per-unit input costs $c_{i,r}$ lead to an increase in the price. The same is true for the trade costs $\delta_{i,r,s}$. The more costly it is to ship good i from r to s, the higher the price in region s. High trade costs impede consumers and firms in region s from purchasing efficiently produced varieties from region r which leads to higher prices. A high absolute productivity, $T_{i,r}$, implies that sector i in region r uses its input bundle efficiently. Thus, prices decrease in $T_{i,r}$. Furthermore, high output taxes $\tau^x_{i,r}$ increase the price $P_{i,s}$.

θ_i is the shape parameter of the Fréchet distribution. A high θ_i implies that productivity draws are similar. If productivities are similar, gains from trade are smaller because a region finds it harder to replace inefficiently produced domestic varieties by more efficiently produced imported ones. Therefore, the sectoral price $P_{i,s}$ increases in θ_i, ceteris paribus.

Next, a trade share $\pi_{i,r,s}$ can be derived. It denotes the share of destination region s's demand for good i which is supplied by origin region r. The trade share $\pi_{i,r,s}$ can be written as follows. See appendix C as well as Caliendo et al. (2014) for the detailed derivation.

$$\pi_{i,r,s} = \frac{T_{i,r}^{\theta_i}(1-\tau^x_{i,r})^{\theta_i}\left(c_{i,r}\delta_{i,r,s}\right)^{-\theta_i}}{\sum_{rr} T_{i,rr}^{\theta_i}(1-\tau^x_{i,rr})^{\theta_i}(c_{i,rr}\delta_{i,rr,s})^{-\theta_i}} \tag{10}$$

The trade share $\pi_{i,r,s}$ measures the share of varieties of good i which region s purchases from region r. Eaton and Kortum (2002) show that $\pi_{i,r,s}$ also corresponds to the share of expenditure on i in s ($D_{i,s}$) which is spent on goods from r. The trade share of region r in s equals r's contribution to the price index.[8]

Plugging the price equation (9) into equation (10) leads to an alternative expression for the **determination of trade shares** which serves as model equation **MQ (6)**.

$$\pi_{i,r,s} = \left[\frac{T_{i,r}(1-\tau^x_{i,r})P_{i,s}}{\gamma_i c_{i,r}\delta_{i,r,s}}\right]^{\theta_i} \tag{11}$$

Equations (10) and (11) illustrate how the trade share of good i from origin region r

[8] Equation (10) reveals that the trade share of good i between regions r and s can only equal zero in two cases. First, if the absolute productivity $T_{i,r}$ of sector i in r equals zero. In this case, r is unable to produce good i. Second, if the trade costs equal infinity ($\delta_{i,r,s} = \infty$) and trade between the regions is impossible. In the numerical solution, however, sufficiently small values are treated as zeros. Therefore, zero trade flows can occur in the model.

to destination region s reacts to a positive shock of the absolute productivity $T_{i,r}$. $T_{i,r}$ enters equation (11) directly, leading to an increase of r's share in s's demand for i. At the same time, the improved productivity $T_{i,r}$ also lowers the price index $P_{i,s}$ (equation 9) leading indirectly to a decrease in the trade share. In summary, a higher $T_{i,r}$ implies an increase in $\pi_{i,r,s}$.

For the interpretation of policy effects, let us derive the following elasticity of the trade share $\pi_{i,r,s}$ with respect to a change in trade costs $\delta_{i,r,s}$.

$$\eta_{\pi_{i,r,s},\delta_{i,r,s}} = \frac{\partial \pi_{i,r,s}}{\partial \delta_{i,r,s}} \frac{\delta_{i,r,s}}{\pi_{i,r,s}} = -\theta_i(1 - \pi_{i,r,s}) \tag{12}$$

The negative sign indicates that higher sector-specific trade costs reduce the corresponding trade share. A larger θ_i and a smaller initial $\pi_{i,r,s}$ go along with stronger policy effects. A high θ_i implies small productivity differences between varieties and thus little leeway for re-allocation as a response to higher trade costs.

2.5 Markets

A well-defined model solution requires that factor, transport, goods and emissions markets are in equilibrium so that all markets clear.

2.5.1 Factors

Consumers supply their endowments of labor and capital inelastically on the factor markets. A market clearing condition determines factor prices $P^F_{f,r}$ by equating the supply and the demand from all sectors. f indexes primary factors, $\tilde{N}_{f,r}$ denotes the exogenous endowment with factor f in r.

Factor demand is derived from the CES production functions displayed in figures 2 and 3. Note that sectors' input bundles do not differ by variety. Thus, the demand for factor f equals the usual CES demand functions (Caliendo et al., 2014). The **market clearing conditions MQ (7)** for the factors labor and capital read as follows. $V_{f,i,r}$ is the endogenous input of factor f in the production of good i in region r.

$$\tilde{N}_{f,r} = \sum_i V_{f,i,r} \ \forall f \in L, K \tag{13}$$

Four sectors employ a sector-specific natural resource in their production: coal ($COAL$), gas ($NGAS$), oil ($CRUD$), and mining ($MINE$). The **market clearing condition MQ (8)** expressed by equation (14) below, determines the price of the natural resource used by sector i in r, $P_{i,r}^{RES}$. It equates the exogenous supply of the resource $\tilde{N}_{RES,i,r}$ with the demand from the corresponding sector $RES_{i,r}$.

$$\tilde{N}_{RES,i,r} = RES_{i,r} \; \forall i \in \{COAL, NGAS, CRUD, MINE\} \tag{14}$$

The next **market clearing condition MQ (9)** determines the price for the technology-specific fixed factor in electricity generation, $P_{g,r}^{FFEG}$ as characterized by equation (15). Here, the exogenous supply of the fixed factor $\tilde{N}_{FFEG,g,r}$ is equated with the demand from technology g in r, $FFEG_{g,r}$.

$$\tilde{N}_{FFEG,g,r} = FFEG_{g,r} \tag{15}$$

2.5.2 Transport

The **market clearing condition** (16) below constitutes **MQ (3)**. It determines the price $P_{h,r}^{T}$ by equating supply and demand for international transport services. The demand for international transport services, which we denote $Z_{h,i,r,s}^{T}$, depends on trade volumes and on $\psi_{h,i,r,s}$.

$$F_h = \sum_{i,r,s} Z_{h,i,r,s}^{T} \tag{16}$$

Let $F_{h,r}$ denote the demand for transportation services from country r by the global transportation sector h. Since the global transportation sector combines its inputs according to a Cobb-Douglas function, the expenditure on transportation services from r can be expressed as:

$$F_{h,r} P_{h,r} = \zeta_{h,r} P_{h,r}^{T} F_h \tag{17}$$

Let $D_{i,s}$ denote the total expenditure of region s on good i. As equation (18) shows, $D_{i,s}$ equals the sum of final ($C_{i,r}$) and intermediate demand for i ($Z_{i,j,r}$). It enters the model as **MQ (10)**.

$$D_{i,s} = \sum_{j} Z_{i,j,s} + C_{i,s} \tag{18}$$

2.5.3 Goods

Goods markets clear when the sales by sector i in region r, $X_{i,r}$, equal the expenditures on its goods in all regions s. Equation (19) shows the **market clearing condition MQ (10)**.

$$X_{i,r} = \sum_s \frac{\pi_{i,r,s} D_{i,s}}{(1+\tau^m_{i,r,s})(1+\sum_h \psi_{h,i,r,s} P^T_h)(1-\tau^e_{i,r,s})} \tag{19}$$

The expression $\pi_{i,r,s} D_{i,s}$ corresponds to the expenditure on goods from i in r by region s. It encompasses both intermediate and final demand. Expenditures on imported goods include trade costs. The denominator of equation (19) corrects the expenditures for export subsidies, international transport margins, and import tariffs. Therefore, the right hand side of equation (19) equals the demand for sector i's goods net of tariffs and international transport margins.

Additional demand for transport services is generated by the global transport services sector. Thus for transport services sectors $h \in i$, the term $\zeta_{h,r} P^T_{h,r} F_h$, derived from the demand function (17), is added to the right hand side of (19).

2.5.4 Emissions

The EU Emissions Trading System (EU ETS) is the key instrument of the European climate policy. Established in 2005, the EU ETS encompasses some 11,000 stationary installations in the EU plus Iceland, Liechtenstein, and Norway. Since 2012 it has also captured parts of the aviation sector. Around 45% of the European Union's CO_2 emissions are covered by the EU ETS (see Ellerman et al., 2010, for an overview).

The price for allowances in the EU ETS, P^{ETS}, is determined by the following **market clearing condition MQ (12)** in equation (20). It equates the exogenous supply of allowances $\tilde{N}^{ETS}$ with the CO_2 emissions by sector i in region r burning fuel j, $A^{CO2}_{j,i,r}, j \in \{COAL, CRUD, NGAS4\}$. This demand is modeled by combining the input of fossil fuels in the nested CES production function with an input of CO_2 allowances in a Leontief nest as illustrated in figures 2 and 3. Note that we restrict the sectors i and regions r to subsets $iets$ and $rets$. The former encompasses all sectors which are part of the EU ETS and the latter all regions which are part of it.

$$\tilde{N}^{ETS} = \sum_j \sum_{i \in iets} \sum_{r \in rets} A^{ETS}_{j,i,r} \tag{20}$$

In the second phase of the EU ETS, between 2008 and 2012, the overwhelming majority of initial allowances were allocated to firms for free. Let $\alpha_{i,r}^{fa}$ denote the share of freely allocated allowances in sector i in r. To replicate free allocation, we introduce an endogenous output subsidy $\phi_{i,r}^{ETS}$ which compensates producers for the sector-specific share $\alpha_{i,r}^{fa}$ of their expenditures on allowances.

$$\phi_{i,r}^{ETS} X_{i,r} = \alpha_{i,r}^{fa} \sum_{j} P^{ETS} A_{j,i,r}^{CO2} \tag{21}$$

This **policy condition MQ (13)** completes the model setup.

3 Calibration

This section describes the calibration procedure and the required data.

3.1 Overview

The advanced trade model as well as the disaggregation of regions and sectors go beyond standard input-output datasets and require elaborated calibration techniques (subsection 3.2). For the trade model, the absolute productivities ($T_{i,r}$) and the iceberg trade costs ($\tilde{\delta}_{i,r,s}$) need to be calibrated via a structural estimation approach. This is a key difference to Armington (1969) based CGE models, in which baseline trade flows are replicated by assuming that they reflect preferences for goods produced in individual regions.

Most other parameter values of the model, such as input shares of CES functions (including Cobb-Douglas and Leontief functions) describing production and consumption as well as tax and subsidy rates, can directly be calibrated to input-output data (subsection 3.3), such as the GTAP dataset (see, for example, Böhringer et al., 2003). Other parameter values, like elasticities of substitution or the share parameter of the Fréchet distribution (θ_i) are taken from the literature.

For the regional disaggregation (subsection 3.4), we adapt and employ a regional science approach (Kronenberg, 2009). Likewise, for the individual representation of the technologies in the electricity sector (subsection 3.5), additional data on the electricity mix and technology-specific inputs are required. A consistent dataset is ensured via a constrained optimization model (following Sue Wing, 2008).

The implementation of the emissions trading scheme involves some specialties, too (subsection 3.6). Beside emissions targets, the regional and sectoral coverage of the scheme as well as the shares of freely allocated allowances must be fixed.

3.2 Trade model

The following subsections explain the structural estimation and the recovery of absolute productivities for the calibration of the trade model.

3.2.1 Structural estimation

Following Eaton and Kortum (2002), we begin by normalizing the trade share $\pi_{i,r,s}$, the share of good i which region s purchases from region r. We divide it by the share of s's consumption of i which is supplied by the domestic industry ($\pi_{i,s,s}$).

$$\frac{\pi_{i,r,s}}{\pi_{i,s,s}} = \frac{T_{i,r}^{\theta_i}(1-\tau_{i,r}^{x})^{\theta_i}\,(c_{i,r}\delta_{i,r,s})^{-\theta_i}}{T_{i,s}^{\theta_i}(1-\tau_{i,s}^{x})^{\theta_i}c_{i,s}^{-\theta_i}} \tag{22}$$

The normalized trade share only depends on parameters of either r or s. It is independent of productivities or trade costs in other regions. Bilateral trade flows and the total demand for good i are observable. Therefore, $\frac{\pi_{i,r,s}}{\pi_{i,s,s}}$ is observable. We linearize equation (22) by taking logs.

$$\begin{aligned}\log\left[\frac{\pi_{i,r,s}}{\pi_{i,s,s}}\right] =& \log\left[T_{i,r}^{\beta_{i,r}\theta_i}(1-\tau_{i,r}^{x})^{\theta_i}c_{i,r}^{-\theta_i}\right] - \\ & \log\left[T_{i,s}^{\beta_{i,s}\theta_i}(1-\tau_{i,s}^{x})^{\theta_i}c_{i,s}^{-\theta_i}\right] - \theta_i\log\left[\delta_{i,r,s}\right]\end{aligned} \tag{23}$$

Recall that the trade costs $\delta_{i,r,s}$ consist of four components (equation 5). Export subsidies ($\tau_{i,r,s}^{e}$), international transport margins ($\psi_{h,i,r,s}P_h^T$), and import tariffs ($\tau_{i,r,s}^{m}$) are observable. Only iceberg trade costs $\tilde{\delta}_{i,r,s}$ need to be estimated.

We use the econometric specification (24) below for the iceberg trade costs. $distance_{r,s}$ denotes the distance between regions r and s. We normalize $distance_{r,s}$ by the shortest distance between two regions in our sample. μ_i is the elasticity of the iceberg costs with respect to distance. Dummy variables capture the effect of sharing a border ($border_{r,s}$), having a common language ($language_{r,s}$), having colonial ties ($colony_{r,s}$), being part of a regional trade agreements ($rtrade_{r,s}$), and having a common currency ($currency_{r,s}$). The parameter $pipeline_{i,r,s}$ is specific to the natural gas sector and captures whether two regions are connected by a gas pipeline.

$$\begin{aligned}\log\tilde{\delta}_{i,r,s} =& \mu_i\log distance_{r,s} + \beta_i^1 border_{r,s} + \beta_i^2 language_{r,s} + \beta_i^3 colony_{r,s} \\ & + \beta_i^4 rtrade_{r,s} + \beta_i^5 currency_{r,s} + \beta_i^6 pipeline_{i,r,s}\end{aligned} \tag{24}$$

Equation (23) can be interpreted as a gravity model of trade (Eaton and Kortum, 2002). It contains technology-cum-input-cost terms for the exporting and the importing nation. We define an exporter fixed effect $e_{i,r} = \log \left[T_{i,r}^{\theta_i} (1 - \tau_{i,r}^x)^{\theta_i} c_{i,r}^{-\theta_i} \right]$ and an importer fixed effect $m_{i,s} = \log \left[T_{i,s}^{\theta_i} (1 - \tau_{i,s}^x)^{\theta_i} c_{i,s}^{-\theta_i} \right]$ which we plug into equation (23). Adding an error term $\varepsilon_{i,r,s}$ yields the following estimation equation. The value of θ_i is taken from the literature.

$$\log \frac{\pi_{i,r,s}}{\pi_{i,s,s}} = e_{i,r} - m_{i,s} - \theta_i \log \delta_{i,r,s} + \varepsilon_{i,r,s} \tag{25}$$

Adding the market clearing condition (19) as a side constraint to the estimation problem ensures that the parameter estimates and, thus, the model's baseline constitute an equilibrium of the model (Balistreri and Hillberry, 2007; Balistreri et al., 2011; Pothen and Balistreri, 2017).

The exporter fixed effect in the United States is assumed zero, $e_{i,USA} = 0$. This implies that we estimate the technology-cum-input-cost terms relative to the USA.

$$S_{i,r} = \exp(e_{i,r}) = \frac{T_{i,r}^{\theta_i} (1 - \tau_{i,r}^x)^{\theta_i} c_{i,r}^{-\theta_i}}{T_{i,USA}^{\theta_i} (1 - \tau_{i,USA}^x)^{\theta_i} c_{i,USA}^{-\theta_i}}. \tag{26}$$

With the help of this expression, we are able to rewrite equation (10) to obtain an expression for $\pi_{i,r,s}$ that solely depends on the trade costs and on $S_{i,r}$.

$$\pi_{i,r,s} = \frac{S_{i,r} \delta_{i,r,s}^{-\theta_i}}{\sum_{rr} S_{i,rr} \delta_{i,rr,s}^{-\theta_i}} \tag{27}$$

In combination with the market clearing condition (19), we obtain a set of equations that we can estimate via Ordenary Least Squares (OLS) (see Appendix D).

3.2.2 Recovering the absolute productivity

Equipped with the estimates of $S_{i,r}$ and $\tilde{\delta}_{i,r,s}$, we calculate relative prices. First, we combine $\tilde{\delta}_{i,r,s}$ with data on import and export tariffs as well as international transport margin to compute the total trade costs $\delta_{i,r,s}$.

The price of good i in region s relative to its United States' counterpart can be written as follows.[9]

$$P_{i,s} = P_{i,USA} \left[\frac{\sum_r S_{i,r} \delta_{i,r,s}^{-\theta_i}}{\sum_r S_{i,r} \delta_{i,r,USA}^{-\theta_i}} \right]^{-1/\theta_i} \tag{28}$$

We conveniently choose units such that the USA's price equals unity in each sector ($P_{i,USA} = 1$). Thereby, we can calculate the prices for all regions. Factor prices $P^F_{f,r}$ are computed by dividing the factor compensation by physical inputs of labor and capital. Prices for the sector-specific natural resources and for the technology-specific fixed factors are normalized to unity. Having derived the sectoral prices, we are able to compute the per-unit input costs $c_{i,r}$.

After computing the per-unit input costs, we can derive the total factor productivity (TFP) $\Lambda_{i,r}$. It can be shown that the TFP can be expressed as $\Lambda_{i,r} = \frac{c_{i,r}}{P_{i,r}(1-\tau^x_{i,r})}$.[10] We plug the TFP term into the expression for trade shares in (11) to obtain:

$$\pi_{i,r,s} = \left[\frac{\Lambda_{i,r} \gamma_i}{T_{i,r}} \right]^{-\theta_i} \tag{29}$$

Solving (29) for $T_{i,r}$ yields the absolute productivities $T_{i,r}$.[11]

$$T_{i,r} = \gamma_i \Lambda_{i,r} \pi_{i,r,s}^{\frac{1}{\theta_i}} \tag{30}$$

3.3 Inputs and outputs

The overall model is designed to match a global input-output dataset as described in the first subsection. The second subsection deals with other data sources.

3.3.1 GTAP data

The most common and most important dataset used for the model calibration is the Global Trade Analysis Project (GTAP) database, version 9 (Aguiar et al., 2016). We calibrate the model to the benchmark year 2011, the most recent one in GTAP 9. The database

[9] Shikher (2012) as well as Levchenko and Zhang (2016) use the formula $\frac{P_{i,s}}{P_{i,USA}} = \left[\frac{\pi_{i,s,s}}{\pi_{i,USA,USA}} \frac{1}{S_{i,s}} \right]^{\frac{1}{\theta_i}}$. Our approach yields the same results but is also applicable to sectors which do not produce and, thus, have $S_{i,s} = 0$.

[10] See, for instance, Caliendo et al. (2014).

[11] Note that estimation problem (47) will lead to different trade flows than those observed in the data. Two adjustments to the data are necessary to balance the inputs and outputs. First, demand for international transportation services is altered due to changing trade flows. We introduce a balancing parameter in the market clearing condition for the international transportation sector to ensure that supply equals demand. Second, the export subsidies paid and the import tariffs received also change. We adjust incomes accordingly.

contains information on input-output structures, bilateral trade flows, and various taxes and tariffs. International transport margins are also provided. GTAP 9 encompasses, furthermore, CO_2 emissions by sector and final demand type.

Data on taxes and tariffs allows researchers to take existing policies into account. The sectoral resolution is sufficient to study substitution between energy carriers in response to energy policies.[12] The 140 regions in GTAP are aggregated to 19 model regions presented in table A2 in appendix A. We distinguish between 17 sectors shown in table A1. Bilateral distances between the aggregated regions are the GDP-weighted average distances between the original regions. Data on GDP is taken from the World Development Indicators.[13]

The structure of GTAP 9 matches the structure of the model. Necessary adjustments concern trade flows within regions. Regions consisting of more than one country exhibit domestic trade flows including tariffs, taxes, and export subsidies. These domestic imports and exports are not compatible with the structure of our model. Hence, we re-allocate tariffs to taxes on intermediate inputs and final demand. Transport margins are re-allocated to regular demand for transport services. Adjustments also concern the regional disaggregation of Germany (subsection 3.4), the disaggregation of the electricity sector (subsection 3.5), and the implementation of the EU ETS (subsection 3.6).

3.3.2 Other sources

Data on bilateral distances, common colonial history, common language, and shared borders are taken from the CEPII GeoDist database (Mayer and Zignago, 2011). Information on regional trade agreement and common currencies stem from de Sousa (2012). The dummy for natural gas pipelines between regions r and s equals one if gas trade via pipeline is observed for 2011. Data for gas trade via pipelines is taken from the International Energy Agency's Natural Gas Information (International Energy Agency, 2015).[14]

Information on employment and employment-to-population ratios is taken from the International Labor Organization's global employment trends report (ILO, 2014). Population data is provided by United Nations (2015).

[12] Other potential sources of data include the World Input-Output Database (WIOD; Timmer et al., 2015) and the EXIOBASE 2 (Wood et al., 2014). The WIOD contains only one extractive sector for fossil fuels and minerals, preventing researchers from modeling inter-fuel substitution. EXIOBASE offers a substantially higher sectoral resolution but a lower regional resolution than GTAP. Both lack the detailed information on taxes and tariffs provided by GTAP.

[13] The only country, for which the World Development Indicators do not report GDP, is Taiwan. Taiwan's GDP is taken from National Statistics of the Republic of China (Taiwan).

[14] International Energy Agency (2015) does not provide data on pipelines between countries. Therefore, we assume that two regions are connected by a pipeline if the data records gas transport via pipeline between these regions.

The elasticities of substitution are taken from the MIT EPPA (Emissions Prediction and Policy Analysis) model (Paltsev et al., 2005). They are listed in appendix B.

3.4 Regional disaggregation

We decompose the German input-output data from GTAP into the Federal State of Lower Saxony (Niedersachsen) and the Rest of Germany. Lower Saxony (LSX) is a large northern state with a high potential for utilizing wind power. We employ the Cross-Hauling Adjusted Regionalization Method (CHARM; Kronenberg, 2009) in the modified version by Többen and Kronenberg (2014) to separate Lower Saxony from the Rest of Germany (ROG). Details can be found in appendix E.1.

Lower Saxony's sectoral composition differs notably from the one in the Rest of Germany (see table E1 in appendix E). Agriculture ($AGRI$) and food production ($FOOD$) account for 1.9% and 3.3% of value added in Lower Saxony compared to 1.2% and 2.4% in the Rest of Germany. Furthermore, the electricity sector ($ELEC$) share of 1.5% is slightly higher than in the Rest of Germany. The share of non-energy intensive manufacturing ($MANU$) and services ($SERV$) is smaller in Lower Saxony than in the Rest of Germany.

3.5 Sectoral disaggregation

The disaggregation of the electricity sector enables an endogenous adjustment of the electricity mix and hence the decarbonization of energy supply induced by climate policy. The technology-specific representation of the electricity generation outlined in subsection 2.3.2 does not have an empirical counterpart in the GTAP data. Hence, we utilize an approach based on Sue Wing (2008) to disaggregate the GTAP data of the electricity sector by generation technology. The required data on electricity output and input shares by technology are taken from the literature. For the following analysis, we disaggregate the electricity sector of Lower Saxony, Rest of Germany, France, Italy and United Kingdom. The full list of regions with and without a disaggregated the electricity sector, is presented in table A2. For other regions, we model an aggregate technology ($gAGG$) which represents all generation technologies. We disaggregate the generation technology by using an algorithm which fits the output of individual technologies and the inputs of labor and value added to the observed data while satisfying the market clearing and zero-profit conditions. The details of the disaggregation are presented in appendix E.2.

3.6 Emissions trading

The EU ETS has been in force since 2005. The GTAP benchmark year 2011 belongs to the EU ETS's second phase which lasted from 2008 to 2012. The GTAP data need to be modified to account for the EU ETS. We combine CO_2 emissions recorded in the GTAP with price data to identify payments for certificates. Furthermore, we calibrate a subsidy $\phi_{i,r}^{ETS}$ which ensures that a free allocation of 90% of the allowances is achieved in the baseline. Details are presented in Appendix F.

4 Policies

The model is tailored to analyze the interaction of trade and climate policy in a globalizing world. Trade liberalization is expected to affect CO_2 emissions and climate policy costs; vice versa climate policy is expected to affect trade and the related productivity gains from specialization. To study these interconnections, in the following subsections we simulate two sets of counterfactual scenarios. First, we study a worldwide reduction of trade costs in terms of tariffs *or* non-tariff barriers (subsection 4.1). Second, we study the reduction of CO_2 allowances in the EU ETS as well as renewable energy support (subsection 4.2).

4.1 Trade policy

In the first set of simulations, we study how changes in trade costs affect welfare and CO_2 emissions. Recall that the trade costs are defined as follows: $\delta_{i,r,s} = (1 + \tau_{i,r,s}^m)(1 + \sum_h \psi_{h,i,r,s} P_h^T)(1 - \tau_{i,r,s}^e)\tilde{\delta}_{i,r,s}$ (equation 5). We implement two scenarios in which we reduce the trade costs.

In the *noTariffs* scenario, $\tau_{i,r,s}^m$ and $\tau_{i,r,s}^e$ are set to zero, i.e., all import and export tariffs or subsidies are abolished in all regions and sectors. The *noTariffs* scenario resembles classical (multilateral) trade agreements under GATT or the auspices of the WTO. Tariffs and subsidies are also one element of currently debated trade agreements, such as the Trans-Atlantic Trade and Investment Partnership (TTIP), or the Trans-Pacific Partnership (TPP).

Table 3 shows the resulting percentage reductions in overall trade costs $\delta_{i,r,s}$ of sectoral trade from r to s in the scenarios *noTariffs* and *lessIceberg*. The reductions range from 1.8% in France to 7.3% in India. For most regions, the drop in trade costs is around two to three per cent.

In recent debates on trade agreements, the reduction of non-tariff trade barriers, such

Table 3
Average reduction in trade costs in the *noTariffs* and *lessIceberg* scenarios

IND	-7.3	*ROE*	-2.3
FSU	-5.7	*USA*	-2.1
CHN	-4.8	*LSX*	-2.0
BRA	-4.3	*ITA*	-2.0
KOR	-4.1	*EUR*	-2.0
ROA	-3.2	*ROG*	-1.9
ROW	-3.1	*CAN*	-1.9
JPN	-2.6	*GBR*	-1.9
OCE	-2.5	*FRA*	-1.8
MEX	-2.3		

All reductions are reported in per cent. Regions are ordered by in ascending order of the reductions. *IND* = India, *FSU* = Former Soviet Union, *CHN* = China incl. Hong Kong, *BRA* = Brazil, *KOR* = South Korea, *ROA* = Rest of Asia, *ROW* Rest of the World, *JPN* = Japan, *OCE* = Australia and Oceania, *MEX* = Mexico, *ROE* = Rest of Europe, *USA* = United States of America, *LSX* = Lower Saxony, *ITA* = Italy, *EUR* = Rest of the European Union, *ROG* = Rest of Germany, *CAN* = Canada, *GBR* = United Kingdom, *FRA* = France.

as product standards or customs procedures, plays a major role. Hence, in the *lessIceberg* scenario, we reduce iceberg trade costs $\tilde{\delta}_{i,r,s}$, which capture such impedemnts to trade, instead of tariffs. To make the *noTariffs* and *lessIceberg* scenarios comparable, we reduce $\tilde{\delta}_{i,r,s}$ to such an extent that the resulting level of overall trade costs $\delta_{i,r,s}$ is the same in both trade scenarios. All other parameters of the model, including the European emissions cap, are held constant in both scenarios.

Table 4 presents the results for the two scenarios in which we reduce trade costs. Welfare effects are measured as changes in real consumption. The change in average domestic supply indicates how trade flows react in the scenarios. The change in TFP reveals how the endogenous productivity is affected by a change in trade costs. Countries' CO_2 emissions, global CO_2 emissions, the CO_2 allowances price in the EU ETS as well as carbon leakage rates indicate the effect of falling trade costs on climate policy. The share of renewable energy in power generation indicates how the electricity sector reacts to trade liberalization. All values are measured as percentage changes between the trade scenario and the baseline with existing trade policies.

The carbon leakage rate is defined as the absolute increase of CO_2 emissions outside the EU ETS divided by the absolute reduction of emissions within the EU ETS. It records the fraction of the emissions reduction in Europe which is compensated by increasing emissions elsewhere.

The change in the carbon leakage rate is estimated as follows. First, we compare the baseline with a simulation in which the number of allowances is drastically increased such that the carbon price drops to zero. This yields the carbon leakage rate in the baseline. Second, we compute the carbon leakage rate for the trade policy scenario with reduced trade costs in the analogous way. Then we compute the percentage change between the leakage rates in the trade policy and baseline scenario.

Table 4 reports the results for six selected regions. The evaluation of Lower Saxony (LSX) with its large wind power potential in comparison to the Rest of Germany (ROG) shows how far the regional disaggregation matters. China (CHN) is chosen as the biggest emerging economy, while the USA are the world's largest economy. Korea (KOR) represents the "Asian Tigers" that have developed with an amazing pace. The Former Soviet Union (FSU) is a major gas supplier to Europe and represents fossil fuel exporters.

In the *noTariffs* scenario, we observe small welfare increases compared to the baseline in most regions. Lower Saxony, the Rest of Germany, China, and the USA exhibit welfare gains of less than one per cent. Korea's welfare increases by 4.3%, which is the strongest rise among all model regions. Its gross income increases by 2.7%, while its true-cost-of-living price index c_s^C falls by 1.6%. Falling trade costs enhance specialization, both within (cf. Finicelli et al., 2013) and between sectors. This specialization causes welfare gains in almost all model regions. Korea benefits particularly from the increased specialization possibilities.

Tariffs can serve as an instrument to exploit power on international markets.[15] If regions abolish welfare-enhancing beggar-thy-neighbor tariffs, they can incur welfare losses. The Former Soviet Union exemplifies this effect. It loses about 2.0% of its welfare due to the removed tariffs.

The average domestic supply, the share of good i, which region r supplies to the domestic market, falls in all regions. Countries increasingly specialize in those activities in which they are productive and import other goods. Consequently, total factor productivity rises in almost all regions in response to removing trade taxes and subsidies. The Former Soviet Union achieves the strongest gain: its TFP grows by 20.9%. To illustrate the specialization gains in a formal way, we solve equation (30) for total factor productivity $\Lambda_{i,r}$ and obtain the following expression:

$$\Lambda_{i,r} = \gamma_i^{-1} \frac{T_{i,r}}{\pi_{i,r,r}^{1/\theta_i}} \tag{31}$$

[15] See Alvarez and Lucas (2007) who study optimal tariffs in an Eaton and Kortum model.

Table 4
Results of the trade policy scenarios

		noTariffs	*lessIceberg*
Welfare	*LSX*	0.46	0.85
	ROG	0.11	0.50
	CHN	0.22	3.09
	FSU	-2.03	8.55
	KOR	4.33	11.57
	USA	0.20	0.50
Average domestic supply	*LSX*	-5.67	-6.01
	ROG	-3.78	-4.12
	CHN	-5.33	-5.41
	FSU	-11.14	-10.60
	KOR	-15.13	-14.99
	USA	-2.28	-2.55
Total Factor Productivity	*LSX*	-0.74	-0.88
	ROG	1.03	0.93
	CHN	3.47	2.82
	FSU	20.93	8.77
	KOR	3.77	3.52
	USA	-0.43	-0.67
CO_2 emissions	*LSX*	-16.38	-16.88
	ROG	-8.50	-8.72
	CHN	-1.74	-2.32
	FSU	-7.94	-2.83
	KOR	34.38	38.64
	USA	1.22	1.34
Renewables share	*LSX*	15.76	15.61
	ROG	14.45	14.60
	CHN	-	-
	FSU	-	-
	KOR	-	-
	USA	-	-
Global CO_2 emissions		2.73	3.40
CO_2 price EU ETS		160	163
Carbon leakage rate		-0.09	-6.07

All changes are compared to the baseline with existing trade costs and reported in per cent. TFP = total factor productivity, *LSX* = Lower Saxony, *ROG* = Rest of Germany, *CHN* = China, *FSU* = Former Soviet Union, *KOR* = South Korea, *USA* = United States of America.

Equation 31 shows that falling domestic supply $\pi_{i,r,r}$ increases total factor productivity ceteris paribus. Sectors specialize in varieties which they manufacture efficiently. This Ricardian selection process (Finicelli et al., 2013) raises TFP.

Some regions, such as Lower Saxony or the United States, experience trade-induced changes in sectoral composition towards less efficient industries. Faced with cheaper foreign competition, these regions expand their production in sectors such as services which have a lower TFP.

The *noTariffs* scenario affects Lower Saxony and the Rest of Germany to different extents. While Lower Saxony exhibits a welfare gain of 0.5%, the Rest of Germany experiences a gain of only 0.1%. The average domestic supply falls more significantly in Lower Saxony than in the Rest of Germany. Apparently, Lower Saxony's economy specializes more intensively in response to falling trade costs. The decline in TFP of 0.7% indicates that Lower Saxony's economy shifts toward less productive sectors.

CO_2 emissions change substantially in response to abolishing tariffs and trade subsidies. In Lower Saxony, they fall by over 16%, which is about twice the reduction of over 8% in the Rest of Germany. This drastic reduction is driven by Lower Saxony's large wind power potential and the resulting low mitigation costs. In the Rest of Germany, China, and the Former Soviet Union, CO_2 emissions fall by less than 10%. On the other hand, the USA and South Korea exhibit rising emissions. In total, global carbon emissions rise by 2.7% due to trade liberalization, while the climate policy-induced carbon leakage rate in the *noTariffs* scenario is almost identical to the one in the baseline.[16] Due to the induced expansion of economic activity, the allowances price in the EU ETS increases by 160% compared to the baseline.

South Korea, whose carbon emissions increase by more than a third, exemplifies how structural change can affect a country's CO_2 emissions. Gross output of the Korean chemicals industry increases by 36%. Other sectors, such as iron and steel, non-ferrous metals and power generation, increase their gross output by more than 20%. Thus Korea's rising CO_2 emissions are driven by structural change in favor of energy-intensive industries.

Table 4 also displays how the share of renewables in power generation changes in response to falling trade costs in Lower Saxony and the Rest of Germany. In the baseline, Lower Saxony has a renewables share in electricity generation of about 30%. The Rest of Germany has a share of about 20%. In both regions, the share of renewables rises by about 16% compared to the baseline. Falling trade costs enhance output and thus carbon emissions. This is reflected by the higher CO_2 price in the EU ETS. The electricity sector reacts to the higher CO_2 price by shifting generation to renewables.

In the *lessIceberg* scenario, the overall trade costs $\delta_{i,r,s}$ are reduced by the same amount as in the *noTariffs* scenario, but the reduction is caused by falling iceberg costs instead

[16] This means, due to trade liberalization emissions rise with and without climate policy so that the leakage rate measured between them stays roughly constant.

of abolished tariffs. Table 4 reveals that reducing the iceberg costs leads to higher welfare gains than dropping tariffs. Welfare gains in the *lessIceberg* scenario are more than twice as high as in the *noTariffs* scenario. Even the Former Soviet Union, which incurred a welfare loss from dropping tariffs, exhibits a welfare gain of 8.6% if iceberg costs are reduced.

The key difference between tariffs and iceberg costs is that tariffs generate revenues which are distributed to the representative consumer, whereas iceberg costs $\tilde{\delta}_{i,r,s}$ constitutes a mere inefficiency. Because regions do not relinquish revenue, their removal leads to stronger welfare gains than eliminating tariffs.

The effects for average domestic supply in the *lessIceberg* scenario are in the same ballpark as in the *noTariffs* scenario. Because trade costs change by the same amount, the trade shares evolve similarly. The TFP grows less substantially when iceberg costs are reduced than when tariffs are abolished. This affect is mainly driven by trade-induced structural change towards sectors with smaller potential for productivity gains: the services sector, for instance, expands more under *lessIceberg* than *noTariffs*.

Within the EU ETS, regional CO_2 emissions fall and the allowances price rises as in the *noTariffs* scenario but with a slightly higher magnitude. Compared to *noTariffs*, renewable power generation slightly shifts from Lower Saxony to the Rest of Germany. Worldwide carbon emissions rise by 3.4% due to the reduction in iceberg costs, which is about 0.7 percentage points higher than under the removal of tariffs.

The climate policy-induced carbon leakage rate falls by 6.1% in the *lessIceberg* scenario compared to the baseline. In the *noTariffs* scenario, on the contrary, we observe an insignificant decrease. With reduced iceberg costs, the EU climate policy is responsible for less carbon leakage to the rest of the world because the reduction of non-tariff barriers supports structural change towards less energy-intensive industries in Europe. This structural change improves energy and carbon efficiency and eases decarbonization within the EU induced by climate policy.

4.2 Climate policy

In the second set of counterfactual simulations, we study how a reduction of allowances in the EU ETS affects welfare, trade, and global CO_2 emissions. All scenarios in this subsection study a 13% reduction of allowances relative to the year 2011. The EU Commission has codified this reduction for the third phase of the EU ETS. The number of allowances will be reduced from 2,084 billion tons in 2011 to 1,816 billion tons in 2020

(EU Commission, 2015). This corresponds to a reduction of emissions covered by the EU ETS by 21% compared to 2005 or 13% compared to 2011.

Four simulations are computed. The first, denoted *ETS20*, corresponds to the 13% reduction of allowances in the EU ETS. All other parameters of the model remain at baseline levels. In other words, the EU ETS's cap is applied to the original baseline data for the year 2011. We do not impose a carbon tax on non-ETS sectors.

In the *ETS20sub* scenario, the reduction of allowances is accompanied by a subsidy for wind power and solar power in the regions Lower Saxony, Rest of Germany, France, Italy and United Kingdom. This scenario reflects that the European 20-20-20 climate policy strategy relies on a mix of instruments. In the EU, particularly in Germany, renewable energies, especially wind and solar power, have been heavily subsidized; in Germany renewable energy levies account for over 20% of households' electricity (Bundesnetzagentur and Bundeskartellamt, 2016). Taking into consideration that the magnitude of support shall be reduced and that the benchmark data already incorporate general taxes and subsidies, we assume a subsidy rate of 10%. In the model, however, electricity generation is not subject to any market failure which would theoretically justify a subsidy (Tinbergen, 1952). Consequently, any additional policy instrument, such as a renewable energy subsidy, is expected to raise the costs of reaching a given emissions target.

The *ETS20gr* scenario takes into account that the emission reduction is envisaged for 2020 and that the economy will grow until then. We assume that the world economy grows by 1.3% per year between 2011 and 2020 (consistent with assumptions for Europe in EU Commission, 2016). This corresponds to an overall growth of 12.3% compared to 2011, i.e., all inputs, outputs, and endowments rise by 12.3%. In the *ETS20gr* scenario, we implement the same absolute reduction goal in the EU ETS as in the *ETS20* scenario.

The last scenario, denoted *ETS20subgr*, combines economic growth and the emissions reduction with a 10% subsidy on wind and solar power in the EU.

Table 5 presents the results of the four scenarios in which the number of allowances in the EU ETS is reduced. It shows changes in welfare (real consumption), average domestic supply, TFP, regions' and global CO_2 emissions, the renewables share in power generation, the allowances' price in the EU ETS, and the carbon leakage rate. All values are expressed as percentage changes relative to the baseline. We display the same regions as in the previous section, except replacing South Korea by France (FRA), the second biggest European economy and member of the EU ETS.

The first column shows the outcomes of the *ETS20* scenario. The emissions reduction does not have major impacts on real consumption. The welfare loss in Lower Saxony amounts to 0.14% and to 0.28% in the Rest of Germany. Welfare falls by only 0.02% in France; with a large nuclear power share, France is hardly affected by the tighter emissions cap. Welfare in Europe's major trade partners such as the USA and China is quasi unaffected. The Former Soviet Union sustains a very small welfare loss due to falling demand for fossil fuels.

Lower Saxony and the Rest of Germany experience a reduction in their average domestic supply by 2.02% and 0.17%, respectively because stricter climate policy raises costs for their industries. Higher costs of carbon make European exports less competitive in other markets such as the Former Soviet Union. These markets display increasing domestic supply, driven by less competition from their European trade partners. The changes in TFP correspond to the changes in average domestic supply (see equation 31): they rise in Lower Saxony and the Rest of Germany but fall in the other regions. This implies climate policy-induced productivity (efficiency) gains in Germany but productivity reductions outside Germany. These policy-induced changes in trade and productivity affect regional emissions and carbon leakage as discussed in the following paragraphs.

CO_2 emissions fall by 18.28% compared to the baseline in Lower Saxony and by 8.32% in the Rest of Germany. Thus, more emissions are abated in Lower Saxony with it's large wind power potential than in the Rest of Germany. The allowances price in the ETS rises by 139% in response to the lower cap. This equals a price of about 45 USD per ton of CO_2. Global CO_2 emissions decrease by 0.27%. Furthermore, the share of renewabales in electricity generation rises in all regions which are subject to the EU ETS. France is less affected than Lower Saxony and the Rest of Germany because its electricity sector is dominated by carbon-free nuclear power. As a result, France's carbon emissions decrease by 2.79%. Slightly increasing emissions in other parts of the world imply carbon leakage. Carbon leakage under the *ETS20* climate policy exceeds the baseline rate by 17.03%.

In the *ETS20sub* scenario, the emissions reduction is accompanied by a 10% subsidy on wind and solar power. Effects on welfare and TFP are almost identical to the *ETS20* scenario. According to our results, the additional policy instrument creates insignificant or minor positive welfare effects. Particularly the Rest of Germany and Italy (not shown in the table) exhibit smaller welfare losses than in the *ETS20* scenario. This effect can be attributed to the interaction with existing taxes and subsidies: in the presence of existing distortions, the welfare effect of a newly introduced instrument is indeterminate ex-ante (Lipsey and Lancaster, 1956). Because electricity inputs in production and consumption

Table 5
Results of the climate policy scenarios

		ETS20 I	*ETS20sub* II	*ETS20gr* III	*ETS20subgr* IV
Welfare	*LSX*	-0.14	-0.14	-0.21	-0.21
	ROG	-0.28	-0.26	-0.61	-0.60
	FRA	-0.02	-0.02	-0.04	-0.04
	CHN	0.00	0.00	0.00	0.00
	FSU	-0.02	-0.03	-0.05	-0.06
	USA	0.00	0.00	-0.01	-0.01
Average domestic supply	*LSX*	-2.02	-0.58	-3.75	-2.10
	ROG	-0.17	-0.10	-0.73	-0.62
	FRA	0.32	0.30	0.58	0.58
	CHN	0.00	0.00	0.01	0.01
	FSU	0.12	0.12	0.26	0.26
	USA	0.07	0.07	0.16	0.15
Total Factor Productivity	*LSX*	0.09	0.09	0.23	0.23
	ROG	0.11	0.10	0.31	0.30
	FRA	-0.16	-0.16	-0.30	-0.30
	CHN	-0.01	-0.01	-0.03	-0.03
	FSU	-0.07	-0.07	-0.19	-0.19
	USA	-0.07	-0.07	-0.17	-0.16
CO_2 emissions	*LSX*	-18.28	-17.05	-30.77	-29.98
	ROG	-8.32	-8.42	-18.18	-18.23
	FRA	-2.79	-2.77	-5.44	-5.43
	CHN	0.24	0.23	0.59	0.57
	FSU	0.70	0.66	1.82	1.76
	USA	0.48	0.46	1.21	1.17
Renewables share	*LSX*	19.22	33.65	42.64	58.01
	ROG	13.58	21.76	34.36	43.33
	FRA	4.97	9.13	11.13	15.53
	CHN	-	-	-	-
	FSU	-	-	-	-
	USA	-	-	-	-
Global CO_2emissions		-0.27	-0.29	-0.47	-0.49
CO_2 price EU ETS		139	133	371	363
Carbon leakage rate		17.03	10.54	35.19	31.04

All changes are measured compared to the baseline without climate policy and reported in per cent. TFP = total factor productivity, *LSX* = Lower Saxony, *ROG* = Rest of Germany, *FRA* = France, *CHN* = China, *FSU* = Former Soviet Union, *USA* = United States of America.

are already taxed, subsidizing wind and solar power generators lowers the overall tax burden on electricity, bringing it closer to the no-tax optimum. Subsidizing domestic renewable energy supply, however, mitigates the reduction of domestic supply (as defined in the previous subsection), which in turn reduces the increase in TFP.

In the *ETS20sub* scenario, CO_2 abatement shifts slightly from Lower Saxony to other regions of Europe, including the Rest of Germany. The share of renewables in electricity generation rises substantially in all regions subject to the EU ETS so that the allowances price rises less strongly than in the *ETS20* scenario. The subsidy encourages the expansion of renewable electricity sources, reducing the price signal needed to achieve the emissions target. In this scenario, we find a reduction of global carbon emissions of 0.29% compared to the baseline without climate policy. This corresponds to an additional reduction of 0.02 percentage points compared to an isolated reduction in the ETS cap (*ETS20* scenario). The renewable energy subsidy reduces the European emissions intensity and lowers mitigation costs. Therefore, the carbon leakage rate under *ETS20sub* increases only by 10.54% compared to the baseline, which is substantially lower than in the *ETS20* scenario.

The *ETS20gr* scenario combines the same absolute emissions reduction as in the previous scenarios with a growing economy over the time horizon 2011 to 2020. The welfare costs of achieving the same absolute emissions level are higher when considering economic growth. Real consumption in Lower Saxony falls by 0.21% and by 0.61% in the Rest of Germany. We do not observe notable welfare changes outside the EU; in the Former Soviet Union, for example, welfare declines by 0.05%.

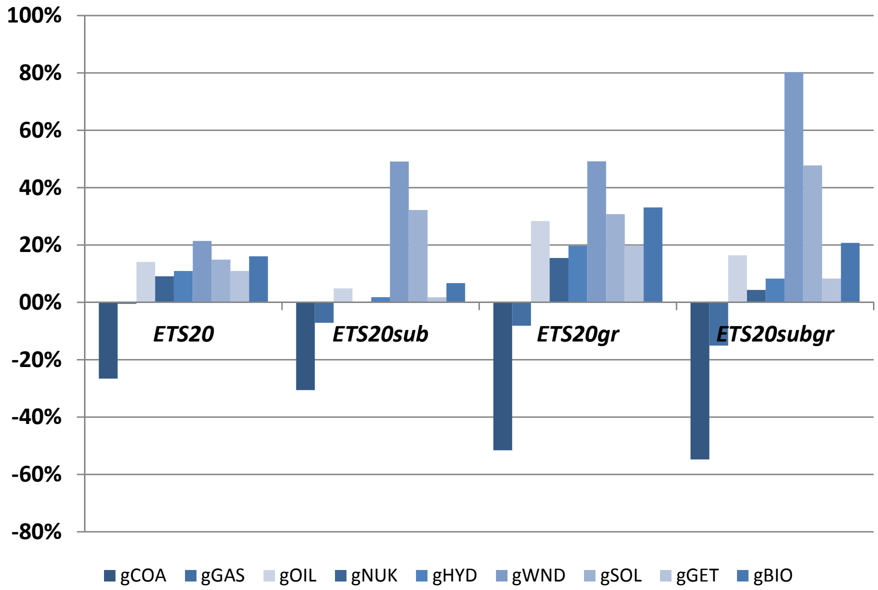
CO_2 abatement is more pronounced in the *ETS20gr* scenario than in the *ETS20* scenario because CO_2 emissions have to fall more substantially to reach the same absolute emission level as in the previous scenarios. In Lower Saxony, carbon emissions fall by 30.77%. Reductions in the Rest of Germany are lower. The allowances price increases by 4.7 times to 88 USD per ton of CO_2. The share of renewables in electricity generation rises by 42.64% in Lower Saxony and 34.36% in the Rest of Germany, but only by 11.13% in France compared to the baseline. We find an increase in the carbon leakage rate of 35.19% compared to the baseline.

Implementing a 10% subsidy for wind and solar power in the *ETS20subgr* scenario has similar effects as in the *ETS20sub* scenario: welfare remains almost unchanged, carbon abatement shifts from Lower Saxony to other parts of Europe, and the allowances price rises less strongly than without the subsidy.

Figure 4 illustrates how the electricity mix in Lower Saxony changes in response to the more ambitious climate policy. The values represent the changes in technology g's value share in electricity generation in per cent compared to the baseline.

In the *ETS20* scenario, the share of electricity generated from coal-fired power plants (gCOA) declines by about 26.6% because coal is the technology with the highest emissions

Figure 4
Change in the electricity mix of Lower Saxony



All changes are measured in per cent relative to the baseline in 2011. The scenarios are defined as *ETS20*: 13% reduction in EU ETS allowances; *ETS20sub*: 13% reduction in EU ETS allowances and 10% subsidies on wind and solar generation in Europe; *ETS20gr*: 13% reduction of EU ETS allowances with growth of 12.3%; *ETS20subgr*: 13% reduction in EU ETS allowances with growth of 12.3% and a 10% subsidy on wind and solar generation in Europe.

intensity. The share of gas (gGAS) falls by less than one per cent. Gas-fired power plants also emit CO_2, but they are less carbon intensive than coal plants. Coal-fired generation is primarily replaced by electricity from renewable sources. All renewable technologies increase their share by 10% or more. The share of solar power rises by 14.9%, the share of wind power by 21.4%.

Introducing subsidies for wind and solar power in the *ETS20sub* scenario alters the way of decarbonization notably. The shares of coal and gas in electricity generation fall more than without the subsidy, by 30.5% and 6.9%, respectively. The share of wind power rises by 48.5% and the share solar power by 29.6% compared to the baseline. The other renewables expand their share in electricity generation by only 2.1% to 7.1%. Thus, the subsidy enhances abatement in the electricity sector by crowding out not only non-renewable energies but also renewables that are not covered by the subsidy. Qualitatively similar patterns emerge in the *ETS20gr* and the *ETS20subgr* scenarios.

5 Conclusion

This article has introduced a complex general equilibrium model tailored for studying the interaction between energy and climate policy on the one hand and international trade policy on the other hand. It combines the theoretical foundations of a Ricardian trade model (Eaton and Kortum, 2002) with the flexibility and expandability of a Computable General Equilibrium model. Notable extensions include Constant Elasticity of Substitution (CES) production and utility functions as well as regional and sectoral disaggregation.

In the currently debated trade agreements, the reduction of non-tariff trade barriers receives more attention than the removal of tariffs. Our results emphasize the benefits of tackling non-tariff barriers. They indicate that the reduction of non-tariff barriers generates larger welfare gains than an equivalent tariff reduction. The worldwide reduction of non-tariff barriers, however, also results in slightly higher CO_2 emissions than the removal of subsidies and tariffs. Nonetheless, there is also good news from an environmental perspective: the reduction of non-tariff barriers induces significant efficiency improvements via specialization, which eases the achievement of the EU emissions cap. This, in turn, reduces carbon leakage from the EU to the rest of the world. Consequently, climate policy negotiators should strive for emissions targets for all important trading economies, as envisaged by the Paris agreement, in order to avoid increasing emissions induced by the removal of non-tariff barriers.

The model distinguishes between the German Federal State of Lower Saxony and the rest of Germany. Lower Saxony is a prime location for renewable electricity generation in Europe and has a notably different sectoral structure than the rest of Germany. It, furthermore, is developing ambitious climate policies (NMUEK, 2016) which are expected to interact with national and international climate policy initiatives as well as with trade policy. Therefore, Lower Saxony constitutes an excellent subject for studying the role of sub-national entities in climate policy.

In both, the trade policy and the climate policy simulations, Lower Saxony is affected to a different extent than the rest of Germany. Its welfare increases more when trade is liberalized while it simultaneously reduces CO_2 emissions by twice as much as the rest of Germany. Due to its large potential for renewable electricity generation and its sectoral structure, Lower Saxony reacts with substantially larger CO_2 abatement to a reduction of allowances in the EU ETS.

As long as there is no global climate policy regime implemented, according to our results, renewable energy support (via a subsidy for wind and solar power) significantly reduces carbon leakage of the European climate policy and slightly reduces global emissions, while the welfare effects are negligible or (in Germany and Italy) slightly positive. These surprising welfare effects can be attributed to the reduction of existing (tax) distortions in a second-best world. Renewable energy support in the EU, however, impairs competition from other regions, which mitigates trade-induced productivity gains from specialization. Such interconnections of climate and trade policy have so far been widely overlooked by economic research and policy.

Like in other numerical model analyses, the estimated magnitudes of policy effects depend on the elasticities of substitution in the CES production and consumption functions and the shape parameter of the Fréchet distribution, which we take from the literature. Thus, we focus on qualitative insights which are robust across different choices of parameter values. In future research, the model can be applied to the analysis of specific regional trade agreements and their effects on CO_2 emissions. Model regions and sectors can be further disaggregated so that, for example, more German federal states and more power generation technologies are visible.

6 Acknowledgement

We gratefully acknowledge funding for the project "NEDS – Nachhaltige Energieversorgung Niedersachsen" supported by the Lower Saxony Ministry of Science and Culture through the "Niedersächsisches Vorab" grant programme (grant ZN3043).

7 References

Aguiar, A., Narayanan, B., and McDougall., R. (2016). An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis*, 1(1):181–208.

Alvarez, F. and Lucas, R. E. (2007). General Equilibrium Analysis of the Eaton-Kortum Model of International Trade. *Journal of Monetary Economics*, 54(6):1726–1768.

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers*, 16(1):159–178.

Balistreri, E. J. and Hillberry, R. H. (2007). Structural Estimation and the Border Puzzle. *Journal of International Economics*, 72(2):451–463.

Balistreri, E. J., Hillberry, R. H., and Rutherford, T. F. (2011). Structural Estimation and Solution of International Trade Models with Heterogeneous Firms. *Journal of International Economics*, 83(2):95–108.

Böhringer, C. (1998). The Synthesis of Bottom-up and Top-down in Energy Policy Modeling. *Energy Economics*, 20(3):233–248.

Böhringer, C., Carbone, J. C., and Rutherford, T. F. (2012). Unilateral Climate Policy Design: Efficiency and Equity Implications of Alternative Instruments to Reduce Carbon Leakage. *Energy Economics*, 34:S208–S217.

Böhringer, C. and Löschel, A. (2006). Promoting Renewable Energy in Europe: A Hybrid Computable General Equilibrium Approach. *Energy Journal*, 27(SI):135–150.

Böhringer, C., Rutherford, T. F., and Wiegard, W. (2003). Computable General Equilibrium Analysis: Opening a Black Box. *ZEW Discussion Paper*, 03-56.

Bosello, F. and Standardi, G. (2015). A Sub-national CGE model for the European Mediterranean Countries. *Research Paper CMCC*, RP0274.

Bundesnetzagentur and Bundeskartellamt (2016). *Monitoringbericht 2016. Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB. Stand: 30. November 2016.* Bundesnetzagentur, Bundeskartellamt, Bonn, Germany.

Bussieck, M. R. and Meeraus, A. (2004). General Algebraic Modeling System (GAMS). In Kallrath, J., editor, *Modeling Languages in Mathematical Optimization*, pages 137–157. Springer US, Boston, MA.

Cai, Y. and Arora, V. (2015). Disaggregating Electricity Generation Technologies in CGE Models: A Revised Technology Bundle Approach with an Application to the U.S. Clean Power Plan. *Applied Energy*, 154:543–555.

Caliendo, L. and Parro, F. (2015). Estimates of the Trade and Welfare Effects of NAFTA. *Review of Economic Studies*, 82(1):1–44.

Caliendo, L., Rossi-Hansberg, E., Parro, F., and Sarte, P.-D. (2014). The Impact of Regional and Sectoral Productivity Changes on the US Economy. *NBER Working Paper*, 20168.

Chen, Y.-H. H., Paltsev, S., Reilly, J. M., Morris, J. F., and Babiker, M. H. (2015). The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. *Joint Program on the Science and Policy of Global Change Reports*, 278.

Costinot, A., Donaldson, D., and Komunjer, I. (2011). What Goods Do Countries Trade? A Quantitative Exploration of Ricardo's Ideas. *Review of Economic Studies*, 79:581–608.

Costinot, A., Donaldson, D., and Smith, C. (2016). Evolving Comparative Advantage and the Impact of Climate Change in Agricultural Markets: Evidence from 1.7 Million Fields around the World. *Journal of Political Economy*, 124(1):205–248.

de Sousa, J. (2012). The Currency Union Effect on Trade is Decreasing over Time. *Economics Letters*, 117(3):917–920.

Dirkse, S. P. and Ferris, M. C. (1995). The PATH Solver: A Non-Monotone Stabilization Scheme for Mixed Complementarity Problems. *Optimization Methods and Software*, 5(2):123–156.

Donaldson, D. (2010). Railroads of the Raj: Estimating the Impact of Transportation Infrastructure. *NBER Working Paper*, 16487.

Eaton, J. and Kortum, S. (1999). International Technology Diffusion: Theory and Measurement. *International Economic Review*, 40(3):537–570.

Eaton, J. and Kortum, S. (2002). Technology, Geography, and Trade. *Econometrica*, 70(5):1741–1779.

Eaton, J. and Kortum, S. (2012). Putting Ricardo to Work. *Journal of Economic Perspectives*, 26(2):65–89.

Ellerman, A. D., Convery, F. J., and de Perthuis, C. (2010). *Pricing Carbon: The European Union Emissions Trading Scheme*. Cambridge University Press, Cambridge.

EU Commission (2015). *EU ETS Handbook*.

EU Commission (2016). *EU Reference Scenario 2016. Energy, Transport and GHG Emissions. Trends to 2050*. Publications Office of the European Union, Luxembourg, Luxembourg.

Finicelli, A., Pagano, P., and Sbracia, M. (2013). Ricardian Selection. *Journal of International Economics*, 89(1):96–109.

Frankel, J. A. and Rose, A. K. (2005). Is Trade Good or Bad for the Environment? Sorting Out the Causality. *Review of Economics and Statistics*, 87(1):85–91.

ILO (2014). *Global Employment Trends 2014: The Risk of a Jobless Recovery*. International Labour Office, Geneva, Switzerland.

International Energy Agency (2015). *Natural Gas Information 2015*. International Energy Agency, Paris, France.

Kortum, S. S. (1997). Research, Patenting, and Technological Change. *Econometrica*, 65(6):1389–1419.

Kronenberg, T. (2009). Construction of Regional Input-Output Tables Using Nonsurvey Methods. The Role of Cross-Hauling. *International Regional Science Review*, 32(1):40–64.

Levchenko, A. A. and Zhang, J. (2016). The Evolution of Comparative Advantage: Measurement and Welfare Implications. *Journal of Monetary Economics*, 78:96–111.

Lipsey, R. G. and Lancaster, K. (1956). The General Theory of Second Best. *Review of Economic Studies*, 24(1):11–32.

Mayer, T. and Zignago, S. (2011). Notes on CEPII's Distances Measures: The GeoDist Database. *CEPII Working Paper*, 2011-25.

Melitz, M. J. (2003). The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity. *Econometrica*, 71(6):1695–1725.

NMUEK (Niedersächsische Ministerium fr Umwelt, Energie und Klimaschutz) (2016). *Szenarien zur Energieversorgung in Niedersachsen im Jahr 2050*. Hannover, Germany. URL: http://www.umwelt.niedersachsen.de/download/106468/Szenarien_zur_Energieversorgung_in_Niedersachsen_im_Jahr_2050_-_Gutachten_-_April_2016_.pdf.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J., Sarofim, M., and Babiker, M. A. M. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. *Joint Program on the Science and Policy of Global Change Reports*, 125.

Peters, G. P. and Hertwich, E. G. (2008). CO2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science & Technology*, 42(5):1401–1407.

Pothen, F. and Balistreri, E. J. (2017). Decomposing the Measure of Ignorance: Total Factor Productivity and Ricardian Selection in the World Economy. *Mimeo*.

Shikher, S. (2012). Putting Industries into the Eaton-Kortum Model. *Journal of International Trade & Economic Development*, 21(6):807–837.

Sue Wing, I. (2008). The Synthesis of Bottom-up and Top-down Approaches to Climate Policy Modeling: Electric Power Technology Detail in a Social Accounting Framework. *Energy Economics*, 30(2):547–573.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Tinbergen, J. (1952). *On the Theory of Economic Policy*. North-Holland Publishing Company, Amsterdam, Netherlands.

Többen, J. and Kronenberg, T. (2014). Construction of Multi-Regional Input-Output Tables using the CHARM method. *Economic Systems Research*, 27(4):487–507.

United Nations (2015). *World Population Prospects: The 2015 Revision*. United Nations, New York, USA. URL: `https://esa.un.org/unpd/wpp/`.

van der Werf, E. (2008). Production functions for climate policy modeling: An empirical analysis. *Energy Economics*, 30(6):2964–2979.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J., Merciai, S., and Tukker, A. (2014). Global Sustainability Accounting - Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability*, 7(1):138–163.

World Bank (2016). *World Development Indicators 2016*. Washington, DC, USA. URL: `http://data.worldbank.org/data-catalog/world-development-indicators`.

Supplementary online appendix

A Definition of sectors and regions

Table A1 lists all sectors between whom we differentiate in the model as well as whether they are part of the EU ETS.

Table A1
Sectors in the model

i	Description	ETS
$AGRI$	Agriculture	No
$COAL$	Coal	No
$CRUD$	Crude oil	No
$NGAS$	Natural gas	No
$PETR$	Refined petroleum	Yes
$FOOD$	Food production	No
$MINE$	Mining	No
$PAPR$	Paper and pulp	Yes
$CHEM$	Chemical products	Yes
$NMMS$	Mineral products nec	Yes
$IRST$	Iron and steel	Yes
$NFMS$	Non-ferrous metals	Yes
$MANU$	Manufacturing	No
$ELEC$	Electricity	Yes
$TRNS$	Transport	No
$CONS$	Construction	No
$SERV$	Services	No

The regions considered in the model are displayed in table A2. The column Disagg indicates whether a technology-specific electricity generation is considered in region r.

Table A2
Regions in the model

r	Description	Disagg	r	Description	Disagg
LSX	Lower Saxony	Yes	CAN	Canada	No
ROG	Rest of Germany	Yes	KOR	Korea	No
USA	United States	No	FSU	Former Soviet Union	No
CHN	China incl. Hong Kong	No	OCE	Australia and Oceania	No
JPN	Japan	No	MEX	Mexico	No
GBR	United Kingdom	Yes	EUR	Rest of the European Union	No
FRA	France	Yes	ROE	Rest of Europe	No
IND	India	No	ROA	Rest of Asia	No
ITA	Italy	Yes	ROW	Rest of the World	No
BRA	Brazil	No			

B Elasticities of substitution

Table B1 lists all elasticities of substitution in the model and their values. The values are taken from (Paltsev et al., 2005). When Paltsev et al. (2005) assume a range of elasticities, the lowest value is chosen. The elasticity of substitution between activities in the electricity sector, σ^{ELE}, is assumed to be zero. This reflects that changes in the electricity grid cannot compensate for changes in electricity demand or supply, at least in the short run. The elasticity of substitution between the fixed factor in electricity generation and the KLF nest ranges from 0.1 (nuclear generation) to 0.6 (wind and solar power).

Table B1
Elasticities of substitution

	Elasticity of substitution between	Value
Final demand and...		
σ^{CE}	Energy goods	0.4
σ^{CN}	Non-energy goods	0.25
σ^{C}	Energy and non-energy aggregates	0.25
Production (non-electricity) and...		
σ^{RES}	KLEM and natural resource	0.6
σ^{KLEM}	KLE and intermediates	0
σ^{KLE}	Value added and energy	0.4
σ^{Z}	Non-energy intermediates	0
σ^{KL}	Capital and labor	1
σ^{E}	Electricity and fossil fuels	0.5
σ^{FF}	Fossil fuels	1
Production (electricity) and...		
σ^{ELE}	Activities	0
σ^{OTD}	Inputs in OTD	0
σ^{GEN}	Technologies	3
$\sigma^{TEC}_{g,r}$	KLF and the fixed factor	0.1-0.6
σ^{KLF}	Value added and fossil fuels	0.4
σ^{KLg}	Capital and labor in generation	1
σ^{FFg}	Fossil fuels in generation	0.3
σ	Varieties	2

C Sectoral price index

The productivity of manufacturing a variety $z_{i,r}$ is a random variable. It is Fréchet distributed with the cumulative distribution function $\Omega_{i,r} = Pr\left[z_{i,r} \leq z\right] = \exp\left[-z^{-\theta_i}\right]$.

The price of variety $z_{i,r}$ purchased in s, $p_{i,r,s}$, is a (linear) function of $z_{i,r}$ and, thus, a random variable itself. $Pr\left[p_{i,r,s} \leq p\right]$ stands for the probability that $p_{i,r,s}$ is below some value p. We can write the distribution of the prices $p_{i,r,s}$ as follows.

$$Pr\left[p_{i,r,s} \leq p\right] = Pr\left[\frac{c_{i,r}\delta_{i,r,s}}{z_{i,r}T_{i,r}(1-\tau^x_{i,r})} \leq p\right] = Pr\left[z_{i,r} \geq \frac{c_{i,r}\delta_{i,r,s}}{pT_{i,r}(1-\tau^x_{i,r})}\right] \tag{32}$$
$$= 1 - Pr\left[z_{i,r} \leq \frac{c_{i,r}\delta_{i,r,s}}{pT_{i,r}(1-\tau^x_{i,r})}\right]$$

The prices $p_{i,r,s}$ can be expressed as follows:

$$Pr\left[p_{i,r,s} \leq p\right] = 1 - \exp\left[-\left(\frac{c_{i,r}\delta_{i,r,s}}{T_{i,r}(1-\tau^x_{i,r})}\right)^{-\theta_i} p^{\theta_i}\right] = 1 - \exp\left[-b_{i,r,s}p^{\theta_i}\right] \tag{33}$$

with $b_{i,r,s} = T^{\theta_i}_{i,r}(1-\tau^x_{i,r})^{\theta_i}\left(c_{i,r}\delta_{i,r,s}\right)^{-\theta_i}$.

Specific varieties produced in different regions are perfect substitutes. Consumers and firms do not prefer varieties produced in one region over those form other regions. Furthermore, we assume perfect competition. Thus, the region r which supplies a variety for the least cost (including trade costs) will supply it to region s. The price of the variety which is actually bought equals:

$$p_{i,s}(z_i) = \min_r\left[p_{i,r,s}(z_{i,r})\right] = \min_r\left[\frac{c_{i,r}\delta_{i,r,s}}{z_{i,r}T_{i,r}(1-\tau^x_{i,r})}\right] \tag{34}$$

With $z_{i,r}$ being Fréchet distributed, the minimum price of a variety z_i in s is distributed as follows.

$$Pr\left[p_{i,s} \leq p\right] = Pr\left[\min_r p_{i,r,s} \leq p\right] = \tag{35}$$
$$= 1 - \prod_r Pr\left[z_{i,r} \leq \frac{c_{i,r}\delta_{i,r,s}}{pT_{i,r}(1-\tau^x_{i,r})}\right]$$

We plug the cumulative distribution function $\Omega_{i,r}$ into equation (35).

$$Pr\left[p_{i,s} \leq p\right] = 1 - \prod_r \exp\left[-\frac{c_{i,r}\delta_{i,r,s}}{T_{i,r}(1-\tau^x_{i,r})}\,p^{-\theta_i}\right] \tag{36}$$
$$= 1 - \exp\left[-\sum_r\left(\frac{c_{i,r}\delta_{i,r,s}}{T_{i,r}(1-\tau^x_{i,r})}\right)^{-\theta_i} p^{\theta_i}\right]$$
$$= 1 - \exp\left[-B_{i,s}p^{\theta_i}\right]$$

with $B_{i,s} = \sum_r T_{i,r}^{\theta_i}(1-\tau_{i,r}^x)^{\theta_i}(c_{i,r}\delta_{i,r,s})^{-\theta_i}$

Equation (36) shows how the realized price of an individual variety is distributed. Equation (37) is the price of the sectoral composite implied by the CES production function (4).

$$P_{i,s} = \left[\int p_{i,s}(z_i)^{1-\sigma}\omega_i(z_i)\ \mathrm{d}z_i\right]^{\frac{1}{1-\sigma}} \tag{37}$$

Equation (36) represents the cumulative distribution function of $p_{i,s}(z_i)$. Its density is $\omega_{i,s} = B_{i,s}\theta_i \exp\left[-B_{i,s}p^{\theta_i}\right]p^{\theta_i-1}$. Plugging the density into equation (37) yields:

$$P_{i,s} = \left[\int p^{1-\sigma}B_{i,s}\theta_i \exp\left[-B_{i,s}p^{\theta_i}\right]p^{\theta_i-1}\ \mathrm{d}p\right]^{\frac{1}{1-\sigma}} \tag{38}$$

Equation (38) is cumbersome to work with. Hence, we employ the change of variables technique and create a new random variable $v = g(p) = B_{i,s}p^{\theta_i}$ to simplify it. The new variable has a density of:

$$\omega^v(v) = \frac{dg^{-1}(v)}{dv}\ \omega(g^{-1}(v)) \tag{39}$$

with $g^{-1}(v) = v^{\frac{1}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}$ and $\frac{dg^{-1}(v)}{dv} = \frac{1}{\theta_i}v^{\frac{1-\theta_i}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}$.
This, v is distributed as follows:

$$\begin{aligned}\omega^v &= \frac{1}{\theta_i}v^{\frac{1-\theta_i}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}B_{i,s}\theta_i\left[v^{\frac{1}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}\right]^{\theta_i-1}\exp\left[-B_{i,s}\left(v^{\frac{1}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}\right)^{\theta_i}\right] \\ &= \theta_i\frac{1}{\theta_i}B_{i,s}B_{i,s}^{\frac{1-\theta_i}{\theta_i}}B_{i,s}^{\frac{-1}{\theta_i}}v^{\frac{\theta_i-1}{\theta_i}}v^{\frac{1-\theta_i}{\theta_1}}\exp\left[-\frac{B_{i,s}}{B_{i,s}}v\right] \\ &= \exp\left[-v\right]\end{aligned} \tag{40}$$

Rearranging the price index equation (37) and plugging in $p = g^{-1}(v)$ as well as its density yields:

$$\begin{aligned}P_{i,s}^{1-\sigma} &= \int v^{\frac{1-\sigma}{\theta_i}}B_{i,s}^{\frac{\sigma-1}{\theta_i}}e^{-v}\ \mathrm{d}v \\ &= B_{i,s}^{\frac{\sigma-1}{\theta_i}}\int v^{\frac{1-\sigma}{\theta_i}}e^{-v}\ \mathrm{d}v\end{aligned} \tag{41}$$

The expression under the integral is Euler's Gamma function evaluated at $1+\frac{1-\sigma}{\theta_i}$. We define $\gamma_i = \Gamma\left(1+\frac{1-\sigma}{\theta_i}\right)^{\frac{1}{1-\sigma}}$. γ_i is a constant that depends only on the elasticity of substitution between varieties σ and on the shape parameter of the Fréchet distribution

θ_i. As long as neither σ nor θ_i are varies in a counterfactual simulation, γ_i only effects the level of the price but not the changes between baseline and counterfactual. The price can then be expressed as:

$$P_{i,s} = \gamma_i B_{i,s}^{-\frac{1}{\theta_i}} = \gamma_i \left[\sum_r T_{i,r}^{\theta_i} (1 - \tau_{i,r}^x)^{\theta_i} (c_{i,r} \delta_{i,r,s})^{-\theta_i} \right]^{-\frac{1}{\theta_i}} \tag{42}$$

Equation (43) displays the elasticity of price $P_{i,s}$ with respect to a change in the absolute productivity $T_{i,r}$ which we denote $\eta_{P_{i,s},T_{i,r}}$. It measures the relative change of $P_{i,s}$ in response to a one percent increase in $T_{i,r}$. The elasticity equals the negative trade share $\pi_{i,rs}$, the share of good i's demand in destination region s which is supplied by origin region r. Thus, the impact of a change in $T_{i,r}$ depends on the share which r has in s's demand. The higher $\pi_{i,r,s}$, the stronger the price reacts to a change in $T_{i,r}$.

$$\eta_{P_{i,s},T_{i,r}} = \frac{\partial P_{i,s}}{\partial T_{i,r}} \frac{T_{i,r}}{P_{i,s}} = - \frac{T_{i,r}^{\theta_i} (1 - \tau_{i,r}^x)^{\theta_i} \, (c_{i,r} \delta_{i,r,s})^{-\theta_i}}{\sum_{rr} T_{i,rr}^{\theta_i} (1 - \tau_{i,rr}^x)^{\theta_i} (c_{i,rr} \delta_{i,rr,s})^{-\theta_i}} = -\pi_{i,r,s} \tag{43}$$

In autarky, the trade share $\pi_{i,s,s}$ equals unity. When neglecting general equilibrium effects, a one per cent increase in productivity will lead to a one per cent decrease in the price. If region s is open to trade, the elasticity $\eta_{P_{i,s},T_{i,r}}$ is always below unity.

The elasticities of price with respect to trade costs and per-unit input costs are $\eta_{P_{i,s},\delta_{i,r,s}} = \pi_{i,r,s}$ and $\eta_{P_{i,s},c_{i,r}} = \pi_{i,r,s}$, respectively. Analogously to $\eta_{P_{i,s},T_{i,r}}$, a one per cent increase in these parameters leads to an increase in price $P_{i,s}$ by $\pi_{i,r,s}$ per cent.

Now we address the following question: What is the probability that region s buys a variety in r? The price of a variety produced in r and bought in s, $p_{i,r,s}$, is distributed as follows:

$$p_{i,r,s} \sim 1 - \exp \left[- \left(\frac{c_{i,r} \delta_{i,r,s}}{T_{i,r} (1 - \tau_{i,r}^x)} \right)^{-\theta_i} p^{\theta_i} \right] \tag{44}$$

Similarly, the price of the same variety supplied by all other regions $rr \neq r$ is distributed:

$$\tilde{p}_{i,rr,s} \sim 1 - \prod_{rr \neq r} \exp \left[- \left(\frac{c_{i,rr} \delta_{i,rr,s}}{T_{i,rr} (1 - \tau_{i,rr}^x)} \right)^{-\theta_i} p^{\theta_i} \right] \tag{45}$$

The variety is bought from r if $p_{i,r,s}$ is lower than $\tilde{p}_{i,rr,s}$ (equation 34). We need to find the probability for that to be the case.

Note that the distribution of prices outlined above implies that $p_{i,r,s}^{\theta_i}$ is exponentially distributed with the parameter $b_{i,r,s}$. Analogously, $\tilde{p}^{\theta_i}_{i,rr,s}$ is exponentially distributed with the parameter $\tilde{B}_{i,s} = \left[\sum_{rr \neq r} T^{\theta_i}_{i,rr}(1-\tau^x_{i,rr})^{\theta_i}(c_{i,rr}\delta_{i,rr,s})^{-\theta_i}\right]$. We can exploit the following property of the exponential distribution: if $p^{\theta_i}_{i,r,s} \sim \exp\left[b_{i,s}\right]$ and $\tilde{p}^{\theta_i}_{i,rr,s} \sim \exp\left[\tilde{B}_{i,r,s}\right]$ are both independently exponentially distributed, then $Pr\left(p^{\theta_i}_{i,r,s} < \tilde{p}^{\theta_i}_{i,rr,s}\right) = \frac{b_{i,r,s}}{b_{i,r,s}+\tilde{B}_{i,r,s}}$. Therefore, the probability that a variety is supplied by r in s is:

$$\begin{aligned}\pi_{i,r,s} &= Pr\left[p_{i,r,s} \leq \min_{rr \neq r} p_{i,rr,s}\right] = \frac{b_{i,r,s}}{B_{i,s}} \\ &= \frac{T^{\theta_i}_{i,r}(1-\tau^x_{i,r})^{\theta_i}\,(c_{i,r}\delta_{i,r,s})^{-\theta_i}}{\sum_{rr} T^{\theta_i}_{i,rr}(1-\tau^x_{i,rr})^{\theta_i}(c_{i,rr}\delta_{i,rr,s})^{-\theta_i}}\end{aligned} \tag{46}$$

D Structural estimation problem

The following set of equations characterizes the structural estimation problem of the trade model under non-linear restrictions. It is implemented as a Non-Linear Programming (NLP) problem in GAMS and solved by using the CONOPT algorithm (Drud, 1985). For sectors which do not produce, we assume $T_{i,r} = 0$. Trade shares smaller than 10^{-8} are excluded from the optimization criterion to avoid numerical problems. The solution yields estimates for $S_{i,r}$ and $\tilde{\delta}_{i,r,s}$.

$$\begin{aligned}
&\min \sum_{i,r,s}\left[\log\frac{\pi_{i,r,s}}{\pi_{i,s,s}} - (e_{i,r} - m_{i,s} - \theta_i \log \delta_{i,r,s})\right]^2 \\
&\text{subject to} \\
&\log \delta_{i,r,s} = \log(1+\tau^m_{i,r,s}) + \log(1+\sum_h \psi_{h,i,r,s}) + \log(1-\tau^e_{i,r,s}) + \log\tilde{\delta}_{i,r,s} \\
&\log\tilde{\delta}_{i,r,s} = \mu_i \log distance_{r,s} + \beta^1_i border_{r,s} + \beta^2_i language_{r,s} + \beta^3_i colony_{r,s} \\
&+ \beta^4_i rtrade_{r,s} + \beta^5_i currency_{r,s} + \beta^6_i pipeline_{i,r,s} \\
&S_{i,r} = \exp(e_{i,r}) \\
&\pi_{i,r,s} = \frac{S_{i,r}\delta^{-\theta_i}_{i,r,s}}{\sum_{rr} S_{i,rr}\delta^{-\theta_i}_{i,rr,s}} \\
&X_{i,r} = \sum_s \frac{\pi_{i,r,s} D_{i,s}}{(1+\tau^m_{i,r,s})(1+\sum_h \psi_{h,i,r,s} P^T_{tr})(1-\tau^e_{i,r,s})} + \zeta_{i,r} F_i \\
&e_{i,USA} = 0
\end{aligned} \tag{47}$$

E Disaggregation procedure

E.1 Regional disaggregation

This subsection describes how Germany (DEU) is decomposed into Lower Saxony (LSX) and the Rest of Germany (ROG). GTAP does not provide data on subnational regions. The latest input-output table for a German Federal State provided by a statistical agency is available for Baden-Wuerttemberg in 1990. Furthermore, some scholars have compiled recent input-output tables for selected Federal States. Examples include North Rhine-Westphalia (Kronenberg, 2009), Mecklenburg-Vorpommern (Kronenberg, 2010), Thuringia (Dettmer and Sauer, 2014), and Baden-Wuerttemberg (Heindl and Voigt, 2012). Schulte in den Bäumen et al. (2015) present research based upon regionally disaggregated input-output data for Germany; the table itself is, however, not publicly available.

We employ a non-survey approach to derive input-output data for Lower Saxony. Non-survey methods have been developed to compile subnational input-output tables with limited primary data, avoiding costly and time-consuming surveys. We rely upon the Cross-Hauling Adjusted Regionalization Method (CHARM; Kronenberg, 2009) in the modified version by Többen and Kronenberg (2014).

E.1.1 Inputs and outputs

We begin by disaggregating final demand. Data on final consumption and investment by Federal State is available at Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder (2015b). We use this data to compute Lower Saxony's shares in final consumption and investment and split them accordingly.[17] The consumption shares in Lower Saxony and in the Rest of Germany are assumed to be the same.

In the next step, we split the gross output of each sector, $X_{i,DEU}$. Data on gross outputs by sector and Federal State is not recorded in Germany. For the oil and gas sectors, physical outputs by Federal State are published by Wirtschaftsverband Erdöl- und Erdgasgewinnung (2012). For electricity generation, the physical output share is computed based upon data from Länderarbeitskreis Energiebilanzen (2016b). For other sectors, we use Lower Saxony's employment share to split the sectors. Employment is measured as the number of employees subject to social insurance contributions ("Sozialver-

[17] An alternative way to compute Lower Saxony's final demand is to employ household survey data such as the Einkommens- und Verbrauchsstichprobe (EVS). It can be used to decompose final consumption by private households, the most important component of final demand (Kronenberg, 2010; Heindl and Voigt, 2012).

sicherungspflichtig Beschäftigte"). Data is compiled by the German Federal Employment Agency (Bundesagentur für Arbeit, 2016a,b).[18]

We assume that all sectors i in Lower Saxony and the Rest of Germany use the same mix of intermediate inputs and primary factors. The intermediate input of good j in sector i in Lower Saxony $Z_{j,i,LSX}$ can then be computed by scaling down the intermediate input of the German sectors ($Z_{j,i,DEU}$) according to Lower Saxony's share in output of i: $Z_{j,i,LSX} = \frac{X_{i,LSX}}{X_{i,DEU}} Z_{j,i,DEU}$. The same procedure is applied to primary factor inputs. We assume that the same tax rates apply in Lower Saxony and in the Rest of Germany.

Table E1 reports the sector shares in value added of Lower Saxony and the Rest of Germany as represented by the model in per cent.

Table E1
Regional sector shares

i	Description	LSX	ROG
$AGRI$	Agriculture	1.9	1.2
$COAL$	Coal	0.0	0.5
$CRUD$	Crude oil	0.1	0.0
$NGAS$	Natural gas	0.2	0.1
$PETR$	Refined petroleum	0.1	0.2
$FOOD$	Food production	3.3	2.4
$MINE$	Mining	0.3	0.1
$PAPR$	Paper and pulp	1.8	1.6
$CHEM$	Chemical products	3.5	3.5
$NMMS$	Mineral products nec	0.8	0.8
$IRST$	Iron and steel	0.5	0.6
$NFMS$	Non-ferrous metals	0.4	0.5
$MANU$	Manufacturing	13.6	15.2
$ELEC$	Electricity	1.5	1.2
$TRNS$	Transport	4.1	3.2
$CONS$	Construction	5.0	4.3
$SERV$	Services	62.9	64.7

Sector shares in value added of Lower Saxony (LSX) and the Rest of Germany (ROG) in per cent. Value added includes payments for natural resources and the fixed factor in the electricity sector.

E.1.2 Trade flows

The next step is to estimate the trade flows of Lower Saxony and the Rest of Germany. Lower Saxony's net exports $N_{i,LSX}$ can be computed by subtracting total demand from gross outputs (equation 48). Both gross outputs $X_{i,LSX}$ and total demand $D_{i,LSX}$ are

[18] For some sectors, in particular agricultural and food-producing industries, the sectoral resolution is lower in the employment data than in GTAP. We use the same share of the more aggregate sector in the employment data for all GTAP sectors. The GTAP sector "dwellings" represents imputed rents. As there is no employment data for this sector, we use Lower Saxony's share in GDP to split it (Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder, 2015a).

already estimated. The net exports in the Rest of Germany are computed analogously.

$$N_{i,LSX} = X_{i,LSX} - D_{i,LSX} = X_{i,LSX} - \left(\sum_j Z_{i,j,LSX} + C_{i,LSX} \right) \tag{48}$$

To calibrate the model, gross trade flows for the new regions need to be estimated. We differentiate between Germany's trade flows and the trade flows between the new regions, Lower Saxony (LSX) the rest of Germany (ROG).

The gross trade flows of Lower Saxony and the Rest of Germany with all other regions are quantified. Data on exports and imports by Federal States for selected goods is available at the German statistical office.[19] We use this data to compute the shares which the two regions have in Germany's imports and exports and split trade flows accordingly. For sectors without primary data, imports are split according to Lower Saxony's share in Germany's total demand for i ($D_{i,LSX}/D_{i,DEU}$) and exports according to Lower Saxony's share in Germany's sales ($X_{i,LSX}/X_{i,DEU}$).

The Cross-Hauling Adjusted Regionalization Method (CHARM; Többen and Kronenberg, 2014) is used to estimate the gross trade flows of Lower Saxony and the Rest of Germany. Cross hauling quantifies the simultaneous exports and imports of good i in r (Flegg et al., 2014). Cross hauling is also known as intra-industry trade in the trade literature.

Cross hauling or intra-industry trade accounts for a substantial share of international trade. If measured at the 5-digit Standard International Trade Classification (SITC), 27% of world merchandise trade was intra-industry trade. If measured at the 3-digit level, this share increases to 44% (Brülhart, 2009). With regions specializing in varieties within sectors, our model allows for intra-industry trade.

Let $H_{i,r}$ denote the cross hauling with good i in region r. $H_{i,r}$ is defined as the sum of exports and imports of i less the absolute value of the net export (equation 49). In other words, it equals the trade volume of i in r minus the absolute value of the net exports. $E_{i,r,s} = \frac{\pi_{i,r,s} D_{i,s}}{(1+\tau^m_{i,r,s})(1+\sum_h \psi_{h,i,r,s} P^T_{tr})(1-\tau^e_{i,r,s})}$ denotes the absolute export of good i from r to s. $M_{i,s,r} = \pi_{i,s,r} D_{i,r}$ is the absolute import of i from s into r.

$$H_{i,r} = \underbrace{(\sum_s E_{i,r,s} + \sum_s M_{i,s,r})}_{\text{Trade volume}} - \underbrace{|\sum_s E_{i,r,s} - \sum_s M_{i,s,r})|}_{\text{Net exports}} \tag{49}$$

[19]Destatis genesis database, "Aus- und Einfuhr (Außenhandel): Bundesländer, Jahre, Länder, Warensystematik". Code 51000-0036.

For any given trade volume, cross hauling or intra-industry trade reaches its maximum when imports and exports offset each other ($\sum_s E_{i,r,s} = \sum_s M_{i,s,r}$). $H_{i,r}$ equals zero if region r only imports or only exports a good.

Let $H^p_{i,LSX,ROG}$ denote the bilateral cross hauling potential between Lower Saxony and the Rest of Germany. It records the upper limit to intra-industry trade between these two regions. It is determined by the minimum of four terms (equation 50): first, the output of good i in Lower Saxony minus exports in all other regions ($X_{i,LSX} - \sum_{s\neq LSX,ROG} E_{i,LSX,s}$). Second, the demand for good i in Lower Saxony minus imports from all other regions ($D_{i,LSX} - \sum_{s\neq LSX,ROG} M_{i,s,LSX}$). Third, the output of good i in the Rest of Germany minus exports in all other regions ($X_{i,ROG} - \sum_{s\neq LSX,ROG} E_{i,ROG,s}$). Fourth, the demand for good i in the Rest of Germany minus imports from all other regions ($D_{i,ROG} - \sum_{s\neq LSX,ROG} M_{i,s,ROG}$). Note that the minimum in equation (50) is multiplied by two. This is necessary because bilateral cross hauling is always double-counted, once as exports and once as imports.

$$\begin{aligned} H^p_{i,LSX,ROG} = 2\min(X_{i,LSX} - &\sum_{s\neq LSX,ROG} E_{i,LSX,s};\\ D_{i,LSX} - &\sum_{s\neq LSX,ROG} M_{i,s,LSX};\\ X_{i,ROG} - &\sum_{s\neq LSX,ROG} E_{i,ROG,s};\\ D_{i,ROG} - &\sum_{s\neq LSX,ROG} M_{i,s,ROG}) \end{aligned} \tag{50}$$

For Germany as a whole, gross trade flows, production and demand for each good i are observable. Hence, we can compute Germany's cross hauling $H_{i,DEU}$ and its cross hauling potential. Let $\chi_{i,DEU}$ denote the share of Germany's cross hauling potential which is realized.

$$\chi_{i,DEU} = \frac{H_{i,DEU}}{2\min\left(X_{i,DEU}; D_{i,DEU}\right)} \tag{51}$$

As an illustration assume, for instance, that Germany has a cross hauling potential of one billion US$ in some sector i. This potential is computed by taking the minimum of Germany's production and total demand for i. Assume, furthermore, that German intra-industry trade with i amounts to 500 million US$. In this example, $\chi_{i,r} = 0.5$ which means that Germany realizes 50% of its cross hauling potential.

We now assume that each region in Germany realizes the same fraction of its cross hauling potential as Germany as whole does ($\chi_{i,DEU} = \chi_{i,LSX} = \chi_{i,ROG}$). Under this assumption, bilateral cross hauling between LSX and ROG equals:

$$H_{i,LSX,ROG} = 2\chi_{i,DEU}\ H^{p}_{i,LSX,ROG} \tag{52}$$

With bilateral cross hauling quantified, we can compute gross exports of i from Lower Saxony to the Rest of Germany, $E_{i,LSX,ROG}$. Bilateral cross hauling is defined as $H_{i,r,s} = E_{i,r,s} + M_{i,s,r} - |N_{i,r}|$. Solving for the trade volume yields $E_{i,r,s} + M_{i,s,r} = H_{i,r} + |N_{i,r}|$. Furthermore, the gross exports of region r can be expressed as $E_{i,r,s} = \frac{E_{i,r,s}+M_{i,s,r}+N_{i,r}}{2}$. Plugging in the trade volume leads to the following formula which we use to compute $E_{i,LSX,ROG}$. It only contains known parameters. Gross exports of the Rest of Germany are computed analogously.

$$E_{i,LSX,ROG} = \frac{H_{i,LSX,ROG} + |N_{i,LSX}|\ + N_{i,LSX}}{2} \tag{53}$$

This step completes the disaggregation of Germany into Lower Saxony and the Rest of Germany.

E.2 Sectoral disaggregation

In the first step of the disaggregation of the electricity sector, all intermediate inputs except coal ($COAL$), natural gas ($NGAS$), and crude oil ($CRUD$) are allocated to an overhead, transmission, and distribution (OTD) activity. See figure 3 which displays the allocation of intermediate and primary factor inputs to the activities in the electricity sector. The input of coal, natural gas, crude oil, as well as value added is distributed among the generation technologies.

To satisfy the accounting identities, the disaggregated electricity sector has to fulfill three sets of restrictions. First, the sum of inputs of factor f in all technologies g, $V_{f,g,r}$, has to equal the input of f into the electricity sector, $V_{f,ELEC,r}$.

$$V_{f,ELEC,r} = \sum_{g} V_{f,g,r} \tag{54}$$

Analogously, the input of coal, gas, and crude oil into the technologies g ($Z_{j,g,r}$) has to equal the input into the electricity sector ($Z_{j,ELEC,r}$). We allocate each of them to one technology. The input of coal is allocated to coal-fired plants ($gCOA$), the input of crude oil to oil-fired plants ($gOIL$) and the input of gas to gas-fired plants ($gGAS$).

$$Z_{j,ELEC,r} = \sum_g Z_{j,g,r} \; \forall j \in \{COAL, NGAS, CRUD\} \tag{55}$$

The third restriction concerns the outputs. The gross output of all technologies ($X_{g,r}$) as well as of the OTD activity ($X_{OTD,r}$) have to equal the output of the electricity sector in GTAP ($X_{ELEC,r}$).[20]

$$X_{ELEC,r} = X_{OTD,r} + \sum_g X_{g,r} \tag{56}$$

We implement two criteria which operationalize the difference between the data and the disaggregated electricity sector (Sue Wing, 2008). Let $\alpha^{tec}_{g,r}$ denote the share of technology g in the total electricity generation of region r. Furthermore, let $\alpha^{v}_{f,g,r}$ denote the input share of primary factor f in technology g.[21] We minimize the following expression (57). Both $\alpha^{tec}_{g,r}$ and $\alpha^{v}_{f,g,r}$ are exogenous parameters. To avoid outliers in the estimated output shares we add the constraint $|\alpha^{tec}_{g,r}| \leq \epsilon_\alpha$ (with $\epsilon_\alpha = 0.2$).

$$\begin{aligned} \min_{X_{g,r}, V_{u,g,r}} \; & \kappa \sum_g \left[\frac{1}{\alpha^{tec}_{g,r}} \frac{X_{g,r}}{\sum_{gg} X_{gg,r}} - 1 \right]^2 + \\ & (1-\kappa) \sum_{g,f} \left[\frac{1}{\alpha^{v}_{f,g,r}} \frac{V_{f,g,r}\left(1+\tau^{v}_{f,g,r}\right)}{X_{g,r}} \right]^2 \end{aligned} \tag{57}$$

The first sum in equation (57) measures the squared difference between g's share in electricity generation in the data and the share of technology g in the total sales of the electricity sector after the disaggregation. Note that $\alpha^{tec}_{g,r}$ is calculated based upon the physical electricity generation, while $\frac{X_{g,r}}{\sum_{gg} X_{gg,r}}$ is the share of g in electricity sales.

The second sum records the differences between the input shares from the data, $\alpha^{v}_{f,g,r}$, and the input share in the disaggregated GTAP data. κ is a weighting parameter which we assume to be 0.9. The problem is implemented as a Non-Linear Programming (NLP) problem in GAMS and solved by using the CONOPT algorithm.

For the disaggregation, we draw on the following data source. The electricity output by technology is taken from the extended world energy balances provided by International Energy Agency (2015). For Germany, we used data on gross electricity generation

[20] The output of technology g is defined as $X_{g,r} = \sum_f V_{f,g,r}(1+\tau^{v}_{f,g,r}) + \sum_j Z_{j,g,r}(1+\tau^{z}_{j,g,r})$. Analogously, the output of the OTD activity is $X_{OTD,r} = \sum_j Z_{j,OTD,r}(1+\tau^{z}_{j,OTD,r})$.

[21] We do not introduce a criterion for the inputs of fossil primary energy carriers. Their inputs are allocated to the respective technology, rendering this criterion uninformative.

by technology and Federal State from Länderarbeitskreis Energiebilanzen (2016a) and Länderarbeitskreis Energiebilanzen (2016b).

The input shares in electricity generation are approximated by input shares in the levelized cost of electricity (LCoE). Schröder et al. (2013) conduct a literature overview and propose a harmonized dataset of LCoE estimates. It contains estimates for the time from 2010 to 2050 and is focused on electricity generation in Europe. Therefore, we use their shares to quantify $\alpha^{v}_{u,g,r}$.

The optimization procedure leads to an electricity mix which is close to the mix reported by the statistical data.

F Emissions trading

This subsection describes the process which is used to implement the European Union Emissions Trading System (EU ETS) as well as the data employed. The CO_2 emissions by sector are taken from the GTAP database. According to the EU Commission, in 2011"7.9 billion allowances were traded, with a value of $147.9 billion" (EU Commission, 2012). This implies an average allowances price of 18.72 USD per ton of CO_2.

In phase I and II of the EU ETS, the overall cap on CO_2 was determined in a bottom-up manner. Member states submitted national allocation plans to the EU Commission which reviewed and then either confirmed or rejected them. The final emissions caps per region added up to 2.08 billion tons of CO_2 per year (EU Commission, 2007) in the second phase. We assume that income from selling allowances is distributed according to the share of each region in the overall cap. The data on the emissions caps by country is taken from EU Commission (2007). We split Germany's cap according to Lower Saxony's share in population.

Based upon this data, the GTAP database is modified in three steps. The first step is to allocate the input of allowances to the fossil fuel nests in the EU ETS sectors. Figures 2 and 3 show how the how allowances and intermediate inputs of fuels are combined.[22]

The following sectors are part of the EU ETS: refined petroleum ($PETR$), paper and pulp ($PAPR$), chemical products ($CHEM$), mineral products not elsewhere classified ($NMMS$), iron and steel ($IRST$), non-ferrous metals ($NFMS$), and electricity ($ELEC$).

[22]Table A1 shows which sectors are assumed to be part of the EU ETS. We assume that the sectors as a whole are covered by the emissions trading scheme. The sectors in the EU ETS are energy-intensive industries dominated by large companies which account for the vast majority of the emissions. Ignoring small firms which are part of these industries but not subject to the EU ETS is unlikely to bias the results.

The second step is to quantify the output subsidy $\phi_{i,r}^{ETS}$. It reflects that the majority allowances were allocated freely to the sectors in the second phase of the EU ETS. We assume that 90% of allowances are freely allocated.[23]

The third step is to balance the ETS sectors' taxes. According to the European System of Accounts 2010 (Eurostat, 2013), payments for allowances are classified as output taxes. In the model, payments for allowances are effectively (endogenous) taxes on fossil fuel inputs. We therefore adjust the output tax rate $\tau_{i,r}^{x}$ to equate payments to the government.

For the sectors which are not part of the EU ETS, we assume that no additional climate policy is introduced beyond measures in force in 2011. Taxes on fossil fuel inputs are recorded in the GTAP data.

G References of the appendix

Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder (2015a). *Bruttoinlandsprodukt, Bruttowertschöpfung in den Ländern der Bundesrepublik Deutschland 2000 bis 2014. Reihe 1, Band 1.* Statistisches Landesamt Baden-Württemberg, Stuttgart, Germany. URL: `http://www.vgrdl.de/`.

Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder (2015b). *Entstehung, Verteilung und Verwendung des Bruttoinlandsprodukts in den Ländern der Bundesrepublik Deutschland. 1991 bis 2014. Reihe 1, Band 5.* Statistisches Landesamt Baden-Württemberg, Stuttgart, Germany. URL: `http://www.vgrdl.de/`.

Brülhart, M. (2009). An Account of Global Intra-industry Trade, 1962-2006. *World Economy*, 32(3):401–459.

Bundesagentur für Arbeit (2016a). *Sozialversicherungspflichtig und geringfügig Beschäftigte nach Wirtschaftszweigen der WZ 2008 in Deutschland.* Statistik der Bundesagentur für Arbeit, Nürnberg, Germany. URL: `http://statistik.arbeitsagentur.de`.

Bundesagentur für Arbeit (2016b). *Sozialversicherungspflichtig und geringfügig Beschäftigte nach Wirtschaftszweigen der WZ 2008 in Niedersachsen.* Statistik der Bundesagentur für Arbeit, Nürnberg, Germany. URL: `http://statistik.arbeitsagentur.de`.

Dettmer, B. and Sauer, T. (2014). Regionalökonomische Auswirkungen eines geplanten Pumpspeicherkraftwerks: Eine Input-Output-Analyse für den Freistaat Thüringen. *Zeitschrift für Energiewirtschaft*, 38(4):255–268.

Drud, A. (1985). CONOPT: A GRG Code for Large Sparse Dynamic Nonlinear Optimization Problems. *Mathematical Programming*, 31(2):153–191.

[23] The European Environment Agency provides data on both freely allocated allowances and verified emissions. These cannot easily be translated into a share of free allocation for two reasons. First, data is recorded by installation and not by sector. Second, the data implies a share of free allocation greater then 100% for most types of installations. The allowances which they received for free exceeded their total emissions.

EU Commission (2007). Emissions trading: EU-wide cap for 2008-2012 set at 2.08 billion allowances after assessment of national plans for Bulgaria. *European Commission Press Releases Database*, IP/07/1614.

EU Commission (2012). *EU ETS 2005-2012*. URL: https://ec.europa.eu/clima/policies/ets/pre2013.

Eurostat (2013). *European System of Accounts 2010*. Publications Office of the European Union, Luxembourg, Luxembourg.

Flegg, A. T., Huang, Y., and Tohmo, T. (2014). Cross-Hauling and Regional Input-Output Tables: The Case of the Province of Hubei, China. *University of the West of England. Economics Working Paper Series*, 1310.

Heindl, P. and Voigt, S. (2012). Employment Effects of Regional Climate Policy: The Case of Renewable Energy Promotion by Feed-In Tariffs. *ZEW Discussion Paper*, 12-066.

International Energy Agency (2015). *Extended World Energy Balances. 2015 Edition*. International Energy Agency, Paris, France.

Kronenberg, T. (2009). Construction of Regional Input-Output Tables Using Nonsurvey Methods. The Role of Cross-Hauling. *International Regional Science Review*, 32(1):40–64.

Kronenberg, T. (2010). Erstellung einer Input-Output-Tabelle für Mecklenburg-Vorpommern. *AStA Wirtschafts- und Sozialstatistisches Archiv*, 4(3):223–248.

Länderarbeitskreis Energiebilanzen (2016a). *Bruttostromerzeugung aus Erneuerbaren Energieträgern in GWh (Stand 31.03.2016)*. Statistisches Landesamt Bremen, Bremen, Germany. URL: http://www.lak-energiebilanzen.de/dseiten/energiebilanzenAktuelleErgebnisse.cfm.

Länderarbeitskreis Energiebilanzen (2016b). *Bruttostromerzeugung nach Energieträgern in GWh (Stand 31.03.2016)*. Statistisches Landesamt Bremen, Bremen, Germany. URL: http://www.lak-energiebilanzen.de/dseiten/energiebilanzenAktuelleErgebnisse.cfm.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J., Sarofim, M., and Babiker, M. A. M. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. *Joint Program on the Science and Policy of Global Change Reports*, 125.

Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., and von Hirschhausen, C. (2013). Current and Prospective Costs of Electricity Generation until 2050. *DIW Data Documentation*, 68.

Schulte in den Bäumen, H., Többen, J., and Lenzen, M. (2015). Labour Forced Impacts and Production Losses due to the 2013 Flood in Germany. *Journal of Hydrology*, 527:142–150.

Sue Wing, I. (2008). The Synthesis of Bottom-up and Top-down Approaches to Climate Policy Modeling: Electric Power Technology Detail in a Social Accounting Framework. *Energy Economics*, 30(2):547–573.

Többen, J. and Kronenberg, T. (2014). Construction of Multi-Regional Input-Output Tables using the CHARM method. *Economic Systems Research*, 27(4):487–507.

Wirtschaftsverband Erdöl- und Erdgasgewinnung (2012). *Jahresberichte Zahlen und Fakten 2012*. Wirtschaftsverband Erdöl- und Erdgasgewinnung e. V., Hannover, Germany. URL: http://www.bveg.de/content/download/3720/38766/file/WEG-Jahresbericht2012.pdf.