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Sector coupling and negative leakage – Unilateral climate policies in the presence of an ETS

Christoph Böhringer* and Carsten Helm†

Abstract

It is widely accepted that the transition towards a zero emissions economy requires to electrify all energy-related processes. In this article, we consider a group of countries for which the electricity sector is governed by an emissions trading system (like the EU-ETS). We then examine unilateral action by a group of environmentally more ambitious countries to support this so-called sector-coupling via a tax on CO₂ emissions in the sectors transport and buildings (heating and cooling). The tax induces a switch to electricity based technologies (e.g., electric vehicles and heat pumps), raises electricity demand and, thus, leads to a higher permit price in the ETS. This raises the costs of CO₂ intensive electricity generation technologies, especially coal, in *all* countries under the ETS. As a result, some of the emission reductions that are triggered by the unilateral tax take place in the other group of countries, i.e., we have *negative* leakage. We examine this in a stylized analytical model and, thereafter, in a substantially more complex CGE model. We find that a unilateral tax of €125 of countries with targets above 25 percent under the EU effort sharing regulation (ESR) results in emission reductions of 3.2 percent in the other group of countries.

Keywords: unilateral action, sector coupling, electrification, negative leakage, overlapping regulation, ETS

JEL Classification: H23, D58, Q54, Q38

1 Introduction

Even within relatively homogeneous groups of countries like the EU, policy approaches to reduce greenhouse gas (GHG) emission are often fragmented. For example, EU climate policies comprise multilateral, harmonized regulation for an emissions trading system (EU-ETS), but this is complemented by unilateral policies, even in the same ETS-sector as, e.g., the subsidization of renewable energies or the phasing out of coal. A substantial literature has shown that such overlapping regulation is not only a potential source of excess cost. It may also be ineffective in achieving the objectives underlying the unilateral action if emission reduction policies in one country lead to emission increases in other countries, often called *positive* leakage. In the case of the EU-ETS, this is sometimes referred to as the waterbed effect.

By contrast, in this paper we analyze unilateral policies in the *non*-ETS sector, with a focus on mobility and heating that currently account for roughly one-third of EU GHG emissions. There exists widespread consensus that this sector needs to be electrified. This “sector coupling” raises electricity demand and, thus, has feed-back effects for the ETS sector. We will show that the effects of this overlapping regulation *across* sectors are much more favourable than those from overlapping policy interventions within the same ETS sector. In particular, such policies often lead to *negative* leakage

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of emissions; i.e., a unilateral non-ETS policy triggers emission reductions not only at home but also in other countries.

In the first part of the paper, we develop a theoretical model to identify the main cross-sector and cross-regional transmission mechanisms at play. The model comprises N countries that each have an ETS sector (electricity) and a non-ETS sector (mobility, heating), both of which operate with a clean and a dirty (fossil) technology. Sector-coupling and the permit market create linkages between sectors and countries, respectively. If one group of countries unilaterally implements an emissions tax in the non-ETS sector, output shifts towards the clean, electricity based technology. The resulting higher electricity demand raises the permit price in the ETS sector and, thus, the costs of the fossil technology *in all* countries that fall under the ETS. For the unilateral-action country we show that emissions fall in the non-ETS sector (mobility) but rise in the ETS sector (electricity), whereas this pattern is reversed in the other countries. Metaphorically speaking, we have a *reverse* waterbed effect, where the unilateral non-ETS policy and the resulting higher permit price increase the pressure on the other side of the waterbed more strongly.

Due to the countervailing effects in the ETS and non-ETS sectors, the effect on aggregate emissions in the individual countries is ambiguous, even though overall emissions unambiguously fall in response to the unilateral action. This is further explored in the second part of the paper, where we apply a computable general equilibrium (CGE) model for the EU economy to substantiate our analytical findings with quantitative evidence based on empirical data. The specific scenario that we consider is inspired by the EU's target to raise emissions reductions from 40 to 55 percent. Specifically, we assume that countries that have accepted higher targets under the effort sharing regulation (ESR) — thus showing a higher ambition level — will unilaterally raise their original ESR reduction target by an additional 32 percent. This corresponds to a unilateral emissions tax of 125€/t. Obviously, this policy has the strongest effect in the countries that implement it, leading to total emission reductions of 18.9 percent in our main scenario. Less obviously, also total emissions in the other regions of the EU fall by 3.2 percent; hence there is *negative* leakage. As regards to emissions in the ETS-sector, these increase in the unilateral action group by 3.1 percent but fall in the other countries by 6.9 percent, thus confirming the reverse waterbed effect. More generally, although the CGE model entails a much more detailed representation of the economic adjustments that follow from the policy intervention, all results are consistent with those in the analytical model. This confirms that the latter does actually capture the most relevant effects for the issue at stake.

Our paper contributes to the growing literature on overlapping regulation in climate policy, but stands out by its focus on the emerging topic of sector coupling. The former literature has focused on policy interventions in the ETS sector. As long as emissions are determined by a given permit endowment — i.e., unless permits are cancelled — there can be no emissions effect in this sector by construction. Moreover, policies like a unilateral coal phase-out or support schemes for renewables tend to lower the ETS price, from which CO₂ intensive power production, especially coal, benefits the most. In line with this, Anke, Hobbie, Schreiber, and Möst (2020) and Böhringer and Rosendahl (2020) point out that without an accompanying cancellation of emissions allowances, a national coal phaseout would depress EU-ETS prices since aggregate emissions remain unchanged, stimulating gas power generation and also coal power in countries without phaseout policies (see also Keles and Yilmaz, 2020).

However, the literature has emphasized that feed-back effects need to be taken into account which result from the interlinkage with other sectors that do not fall under the ETS. An early contribution is Baylis, Fullerton, and Karney (2014) who examines this analytically using a two-sector model, where the carbon tax in one sector is increased (see also Baylis, Fullerton, and Karney, 2013). They even find negative leakage because the taxed sector draws resources away from the other sector or country, which reduces their output and emissions. Accordingly, this mechanism is based on standard general equilibrium effects, rather than on the implications of sector coupling as in our paper. Moreover, Winchester and Rausch (2013) investigate this leakage mechanisms in a CGE model and show that fossil fuel supply elasticities must be close to infinity to generate net negative leakage, whereas empirical estimates for fossil fuel supply elasticities are less than 1.

Jarke and Perino (2017) extend the model of Baylis et al. by considering two technologies (clean and dirty) instead of one in the capped sector. They then analyze the effects of policies (ETS for electricity sector, carbon tax in non-electricity sector, FIT for green electricity) that drive substitution between them. Our analytical model goes one step further by also considering two technologies in the non-ETS sector. Two further contributions of these authors use similar models but consider different policies: climate campaigns in Perino (2015) as well as energy promotion in Jarke-Neuert and Perino (2020). Eichner and Pethig (2019; 2021) share our focus on the EU-ETS and emphasize that a unilateral coal phase-out and green energy promotion may raise emissions in other regions (positive leakage). Finally, Jarke-Neuert and Perino (2019) is closest to our article in that they also consider sector coupling. However, they essentially have a one-country model; hence they do not examine the spillover effects of unilateral policies on other regions and the resulting negative leakage effects that are central for our paper. Moreover, although some of these above articles complement a theoretical analysis with numerical simulations, this is not done within a fully fledged CGE model.

2 Analytical model

Consider a set of $N = \{1, \dots, n\}, n \geq 2$ countries that are indexed i . We split the economy of each country into an ETS-sector that comprises all economic activities whose emissions are regulated by an emissions trading system (ETS), and a non-ETS sector that comprises the rest of the economy. For parsimony, we assume that the only output of the ETS-sector is electricity (denoted y), and that the output of the non-ETS sector (denoted x) has the potential for “electrification” (sector-coupling). Mobility and heating are the most relevant activities in this respect. Therefore, we often refer to the ETS and non-ETS sectors simply as electricity and mobility, respectively. In each sector, there is one representative firm that produces with a “clean” (indexed c) technology and one that uses a “dirty” (indexed d) technology. Accordingly, y_{ci} is electricity output that has been produced with the clean technology in region i , and so on. The dirty technologies use fossil fuels as an input; e.g., coal plants for electricity generation, conventional vehicles and oil heating systems. By contrast, the clean technologies are based on renewable energies in the ETS-sector and on the replacement of fossil fuels by electricity in the non-ETS sector.¹

Total mobility and electricity production are then $x_i = x_{ci} + x_{di}$ and $y_i = y_{ci} + y_{di}$. Note that here and in the remainder we skip the addendum “for $i \in N$ ” whenever no confusion can arise. Emissions that result from production in the dirty sectors are denoted e_{xi} and e_{yi} , respectively. We assume that they are proportional to output, yielding $e_{xi} = \alpha_{xi}x_{di}$ and $e_{yi} = \alpha_{yi}y_{di}$, where $\alpha_{xi}, \alpha_{yi} > 0$ are the emission intensities of the two sectors. These are given exogenously, which implies that emissions in the dirty sectors can only be reduced by restricting output. Obviously, this is a strong simplification that neglects the possibilities of efficiency improvements and of switching to less CO₂ intensive energy carriers (e.g. from coal to gas). Nevertheless, it reflects the relatively mature status of conventional fossil technologies and our focus on the incentives to switch to the clean, renewables-based technologies. Given this simplification, we can denote the cost functions that result from firms’ cost minimization problems in the electricity and dirty mobility sectors by $C_{ci}^y(y_{ci})$, $C_{di}^y(y_{di})$, and $C_{di}^x(x_{di})$.²

Clean mobility is special in that it uses electricity and, thus, an output of the other sector as input. This link between the two sectors is crucial for our analysis so that we explicitly account for it, in contrast to the other inputs. Moreover, we assume that electricity input in the non-ETS sector is proportional to output. This appears reasonable if one thinks of mobility as mileage driven and of heating as thermal energy provided. Therefore, we split up the value function of the cost minimization problem into the two components $C_{ci}^x(x_{ci}) + p_{yi}y_{xi}$, where $y_{xi} = \beta x_{ci}$ is electricity input to produce

¹ Obviously, this simple labelling neglects that (i) the production of wind mills, solar panels and electric vehicles usually leads to substantial CO₂ emissions, and that (ii) the electricity that drives electric vehicles may have been generated by using fossil fuels. However, the latter emissions will be accounted for in the electricity sector, and production emissions will be included in the later numerical simulations.

² For a description how these cost functions can be derived from a general cost minimization problem with labour and capital inputs under standard convexity assumptions see Phaneuf and Requate (2016, Section 5.1.1).

x_{ci} units of clean mobility and p_{yi} is the price of the electricity input. Accordingly, a higher β can be interpreted as a technology that is less efficient in converting electricity into mobility or heating services.

We adopt the standard assumption that all cost functions are twice continuously differentiable with $C'_{ki}(\cdot) > 0$ and $C''_{ki}(\cdot) \geq 0$, $k = c, d$. Note that, in slight abuse of notation, we have dropped the superscript because the arguments x_{ki}, y_{ki} clarify to which sector the cost functions belong. Mobility (and heating) depends on location and, therefore, is assumed to be traded on national markets at prices p_{xi} . For electricity, there exists cross-country trade, especially in some regions in the EU. Nevertheless, national markets are often largely separated, also due to the lack of sufficient transmission capacities. In the later numerical simulation we explicitly account for this “partial” tradability, but in the analytical model we focus on national electricity markets and denote electricity prices by p_{yi} . This choice is also motivated by our intention to focus on the effects of sector coupling via the ETS, rather than via changes in the trade patterns of electricity.

In each country, there is a representative household that maximizes its quasilinear utility $U_i(x_i, y_i, z_i) = u_i^x(x_i) + u_i^y(y_i) + z_i$ subject to the budget constraint $p_{xi}x_i + p_{yi}y_i + z_i \leq m$, where z_i is spending on all other goods (price normalized to 1), and m is income. As for cost functions, we drop superscripts x, y for parsimony and assume that $u_i(x_i)$ and $u_i(y_i)$ are increasing and concave. Accordingly, households care about their consumption levels of mobility and electricity, where the latter can be interpreted loosely as the consumption of goods that require considerable amounts of electricity – like cooking, and washing machines. However, consumers have no preferences regarding production technologies.

As mentioned above, we assume that the electricity sector is regulated by an international ETS with auctioned permits, an exogenous emission cap \bar{e}_y , and an endogenous permit price ν . Moreover, let A denote the country that implements a unilateral emissions tax $\tau_A > 0$ in the non-ETS sector ($\tau_i = 0$ for all other countries $i \in N \setminus A$). Altogether, this yields the profit functions for the respective firms, which are given as the difference between revenues, production costs and payments for emissions (π_{di}^y are profits of the representative firm in the dirty electricity sector of country i , and so on):

$$\pi_{di}^y = p_{yi}y_{di} - C_{di}(y_{di}) - \nu e_{yi}, \quad (1)$$

$$\pi_{ci}^y = p_{yi}y_{ci} - C_{ci}(y_{ci}), \quad (2)$$

$$\pi_{di}^x = p_{xi}x_{di} - C_{di}(x_{di}) - \tau_i e_{xi}, \quad (3)$$

$$\pi_{ci}^x = p_{xi}x_{ci} - C_{ci}(x_{ci}) - p_{yi}\beta x_{ci}. \quad (4)$$

Using $e_{yi} = \alpha_{yi}y_{di}$ and $e_{xi} = \alpha_{xi}x_{di}$, profit maximization yields the following first-order conditions for $i \in N$:

$$p_{yi} = C'_{di}(y_{di}) + \nu \alpha_{yi}, \quad (5)$$

$$p_{yi} = C'_{ci}(y_{ci}), \quad (6)$$

$$p_{xi} = C'_{di}(x_{di}) + \tau_i \alpha_{xi}, \quad (7)$$

$$p_{xi} = C'_{ci}(x_{ci}) + p_{yi}\beta. \quad (8)$$

They have the familiar interpretation that marginal production costs equal prices after accounting for the policy instruments. Moreover, in each of the two sector these marginal costs are the same for the dirty and the clean technology. Turning to consumers, the budget constraint obviously binds. Solving it for z and substitution into the utility function yields the first-order conditions that marginal utility equals prices for $i \in N$:

$$\frac{\partial u_i(y_i)}{\partial y_i} = p_{yi}, \quad (9)$$

$$\frac{\partial u_i(x_i)}{\partial x_i} = p_{xi}. \quad (10)$$

Prices follow from the respective market clearance conditions that demand equals supply. These are for the permit market (using $e_{yi} = \alpha_{yi}y_{di}$)

$$\sum_{i \in N} \alpha_{yi}y_{di}(\nu) = \bar{e}_y, \quad (11)$$

for the non-ETS sector (mobility)

$$x_i(p_{xi}) = x_{di}(p_{xi}) + x_{ci}(p_{xi}), \quad i \in N, \quad (12)$$

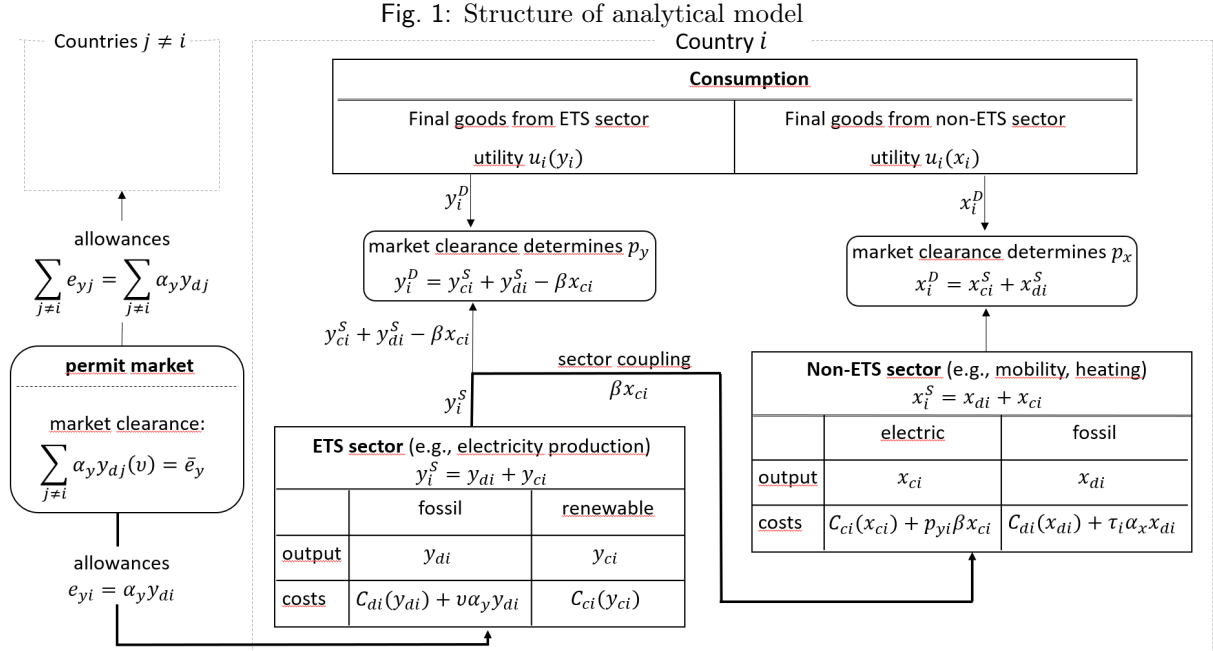
and for the ETS sector (electricity)

$$y_i(p_{yi}) = y_{di}(p_{yi}) + y_{ci}(p_{yi}) - \beta x_{ci}, \quad i \in N, \quad (13)$$

where $\beta x_{ci} = y_{xi}$ is electricity input into clean mobility. This yields a system of 17 equations that determines the 17 endogenous variables (8 output values, 4 consumption values and 5 prices).

3 Effects of unilateral emissions pricing in the non-ETS sector

Figure 1 illustrates the analytical model graphically. Production takes place in the ETS and non-ETS sectors, both of which have a fossil and a non-fossil technology. Preferences over the final goods from these sectors are independent of production technologies and the respective market clearance conditions determine the equilibrium price.



The ETS sector requires emission allowances as an input. These are traded on an international permit market, leading to a “linkage between countries” as represented by the left bold arrow labelled “allowances”. In the analytical model with no trade in mobility and electricity, this is the only link between countries. Moreover, within each country i , the output of the ETS sector enters as an input to the clean (electricity-based) technology in the non-ETS sector. This “linkage between sectors” is represented by the right bold vector labelled “sector coupling”. These two interlinkages drive the

indirect effects that the unilateral tax on the dirty technology in the non-ETS sector has on the other sectors and countries.

The following proposition identifies how these effects change the output and consumption values as well as prices that arise in response to a unilateral tax. In particular, we compare for each of the two countries the situation before and after introducing a unilateral emission tax in the non-ETS sector. These differences are denoted by Δ . Specifically, let \tilde{y}_i and y_i be the respective output with and without the unilateral tax. Then $\Delta y_i := \tilde{y}_i - y_i$ denotes the change in output, and equivalently for the other variables. Note that this approach includes larger changes that result from a larger unilateral tax – such as the one that we will consider in the numerical simulations. By contrast, most of the literature focuses on marginal changes, using either the tools of total differentiation (Eichner and Pethig, 2021) or of log-linearization (e.g., Baylis et al. (2013); Baylis et al. (2014); Jarke-Neuert and Perino (2019)). In the proofs we briefly discuss that our analytical results could also be derived based on these methods.

Proposition 1. *(Comparison with and without unilateral tax) Let A denote the country (or group of countries) that unilaterally raises the tax on emissions in the non-ETS sector; i.e., $\Delta\tau_A > \Delta\tau_j = 0$, where we use the index j for all other countries $i \in N \setminus A$ that do not raise the tax.*

- a) *The permit price in the ETS-sector as well as output prices in both sectors rise ($\Delta\nu > 0$ and $\Delta p_{yi}, \Delta p_{xi} > 0, i \in N$).*
- b) *Effects in non-ETS sector (mobility): Output of the dirty technology falls in country A where it is taxed unilaterally, but rises in the other countries ($\Delta x_{dA} < 0, \Delta x_{dj} > 0$). By contrast, output of the clean technology rises in country A but falls in the other countries ($\Delta x_{cA} > 0, \Delta x_{cj} < 0$). Overall output and, thus, consumption, fall in all countries ($\Delta x_i < 0, i \in N$).*
- c) *Effects in ETS sector (electricity): Output of the dirty technology rises in country A , but falls in the other countries ($\Delta y_{dA} > 0, \Delta y_{dj} < 0$). In all countries, output of the clean technology rises ($\Delta y_{ci} > 0, i \in N$), whereas consumption falls ($\Delta y_i < 0, i \in N$) because the clean non-ETS sector requires more electricity input.*

Intuitively, a unilateral tax of country A on dirty mobility induces a shift from dirty to clean mobility, hence $\Delta x_{dA} < 0$ and $\Delta x_{cA} > 0$. As clean mobility requires more electricity, production from both dirty and clean sources goes up so that $\Delta y_{dA}, \Delta y_{cA} > 0$. In order to induce firms in country A to produce more electricity, the associated price must be higher ($\Delta p_{yA} > 0$). This makes production of clean mobility, which uses electricity as an input, more expensive. Together with the tax on dirty mobility, the price of mobility rises ($\Delta p_{xA} > 0$). Moreover, the higher supply of dirty electricity drives up the permit price ($\Delta\nu > 0$), which makes production of dirty electricity in the other countries more expensive. Hence their supply falls ($\Delta y_{dj} < 0$) which is (partly) compensated by more clean electricity ($\Delta y_{cj} > 0$). Finally, given that the higher permit price raises production cost of electricity, its price goes up ($\Delta p_{yj} > 0$), which makes electricity powered clean mobility more costly. Hence it falls ($\Delta x_{cj} < 0$) and the mobility price rises ($\Delta p_{xj} > 0$), which makes dirty mobility more profitable ($\Delta x_{dj} > 0$).

We now turn to the analysis of emissions, whose reduction is the underlying objective of the unilateral tax in the non-ETS sector (mobility). By assumption, there is a deterministic relation between the output of the dirty technologies and associated emissions. Therefore, the latter follow straightforwardly from $\Delta e_{yi} = \alpha_y \Delta y_{di}$ and $\Delta e_{xi} = \alpha_x \Delta x_{di}$, using the results in Proposition 1. Moreover, there we have seen that the unilateral tax in the non-ETS sector does not only reduce the output of the dirty technology – and, thus, country A 's emissions in that sector. Due to sector coupling, there are also feedback effects on the ETS sector, and on both sectors in the other countries. In particular, their output of dirty – i.e., fossil fuel based – electricity production and associated emissions falls, which constitutes *negative leakage*. By contrast, their output and emissions of dirty mobility rise, constituting *positive leakage*.

Moreover, the aggregate effect on emissions in the ETS-sector is zero due to the cap in this sector. Thus, the overall emission effect is determined in the uncapped non-ETS sector. A priori, this is ambiguous because country A 's unilateral tax reduces domestic emissions from mobility but raises those in the other countries. Nevertheless, one would expect that the direct effect of the tax dominates. The following proposition proves that this is indeed the case and summarizes the above results.

Proposition 2. *(Comparison of emissions and aggregate effects) Let A denote the country (or group of countries) that unilaterally raises the tax on emissions in the non-ETS sector; i.e., $\Delta\tau_A > \Delta\tau_j = 0$, where j is the index for all other countries.*

- (a) *In country A , emissions fall in the non-ETS sector (mobility) but rise in the ETS-sector (electricity) ($\Delta e_{xA} < 0, \Delta e_{yA} > 0$). In the other countries $j \in N \setminus A$, this pattern is reversed ($\Delta e_{xj} > 0, \Delta e_{yj} < 0$).*
- (b) *Overall emissions and the overall output of the dirty technology in the non-ETS sector fall ($\Delta e < 0, \sum_{i \in N} \Delta x_{di} < 0$), whereas overall output of the clean technology rises ($\sum_{i \in N} \Delta x_{ci} > 0$).*

4 Numerical analysis

The theoretical analysis identifies important drivers for economic and emissions effects induced by unilateral pricing of emissions in the non-ETS sectors. However – for the sake of analytical tractability – the theoretical model is quite stylized and misses several real-world features that are potentially important for drawing viable policy conclusions. For example, countries are not only linked via the ETS emissions market but engage in bilateral trade on commodity markets, which creates additional international spillover effects. Moreover, economic adjustments triggered by the policy intervention are driven through substitution, output and income effects that are substantially more complex than in the analytical model with its simple specification of preferences and production sectors. We therefore complement our theoretical analysis with computable general equilibrium (CGE) simulations based on empirical data.

The strength of CGE models is their rigorous microeconomic foundation in Walrasian equilibrium theory, which accommodates the comprehensive welfare analysis of market supply and demand responses to policy shocks. Quantitative equilibrium analysis provides counterfactual ex-ante comparisons, assessing the outcomes with a reform in place against a reference situation without such a reform. Below, we first provide a non-technical summary of the CGE model and its parameterization. We then lay out our counterfactual scenarios rooted in actual EU climate policy design, discuss simulation results, and relate them to those of the analytical model.

4.1 Model description

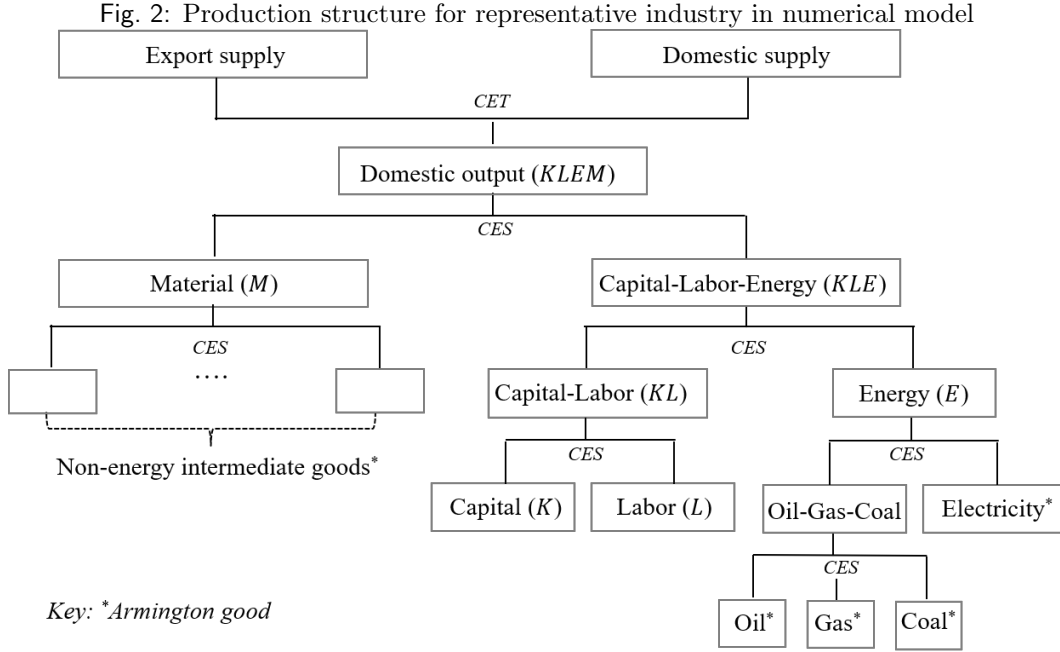
Our multi-sector multi-region CGE model adopts a standard top-down structure for representing production, consumption, and trade, but stands out for a discrete representation of alternative power generation technologies and an explicit integration of sector-coupling possibilities. For the sake of brevity, we limit ourselves to a non-technical model summary. An algebraic model formulation with the detailed specification of functional forms can be found in the Appendix.

4.1.1 Non-technical model summary

Decisions about the allocation of resources are decentralized, and the representation of behaviour by consumers and firms follows the standard microeconomic optimization framework: (i) consumers maximize welfare through private consumption subject to a budget constraint; (ii) firms combine intermediate inputs and primary factors at least cost for given technologies. Preferences and technologies are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to changes in relative prices.

Primary factors of production include labor and capital which are assumed to be mobile across sectors within each region but not internationally. Specific resources are tied to the production of fossil fuels (coal, natural gas, and crude oil) as well as electricity generation by different power technologies. Factor markets are perfectly competitive.

All commodities except for fossil fuels and technology-specific electricity are produced according to a four-level nested constant-elasticity-of-substitution (CES) cost function combining inputs of capital (K), labor (L), energy (E), and material (M) – see Figure 2. At the top level, a material composite (M) trades off with an aggregate of capital, labor, and energy (KLE). At the second level, the material composite splits into non-energy intermediate goods, whereas the aggregate of capital, labor and energy splits into a value-added composite (KL) and the energy component (E). At the third level, capital and labor inputs enter the value-added composite subject to a constant elasticity of substitution. Likewise, within the energy aggregate, electricity trades off with the composite of fossil fuels (coal, natural gas, and refined oil). At the fourth level, a CES function describes the substitution possibilities between coal, refined oil, and natural gas. The output in each production sector is allocated either to the domestic market or the export market according to a constant-elasticity-of-transformation (CET) function.



The production structure of extractive fossil fuel sectors (crude oil extraction, coal mining, natural gas extraction) is captured by a two-level nested CES function where the specific natural resource trades off at the top level with a Leontief composite of all other inputs. The substitution elasticity between the specific factor and the Leontief composite is calibrated to match exogenously chosen supply elasticities.

The technological options in the power sector are of paramount importance for the decarbonization of economic activities. On the one hand, coal and gas power plant are (still) a major source of CO₂ emissions in many countries. On the other hand, electricity generation by renewable energy sources (RES-E) does not only provide an option to substitute fossil-fuel based power production but is also key to sector coupling, i.e. the greening of energy demand in other sectors. We therefore distinguish different power generation technologies that produce electricity by combining inputs of labor, fuel, and materials with technology-specific resources (capital embodied in power plants and natural resources such as water, sun, wind, biomass). For each technology, power generation takes place with decreas-

ing returns to scale and responds to changes in electricity prices according to technology-specific supply elasticities. Within each region, electricity output from different technologies is treated as a homogeneous good which enters as an input to the regional distribution and transmission electricity sector.

Reflecting the fundamental idea of sector coupling there are technological options to substitute energy demands of fossil fuels (coal, oil and gas) directly by electricity (see Figure 2). Such power-to-X technologies are represented as upward slopping supply curves where electricity inputs trade off with technology-specific resources at a constant elasticity of substitution. The latter in accordance with exogenous supply elasticities that capture the ease of sector coupling for the specific energy demand in intermediate and final use.

Final consumption stems from a representative agent in each region who receives income from primary factors and maximizes welfare subject to a budget constraint. Substitution patterns within the consumption bundle of the representative agent are described through a nested CES function which follows the same structure as the production functions of non-resource goods. Government and investment demand are fixed at exogenous real levels. Investment is paid by savings of the representative agent while taxes pay for the provision of public goods and services.

Bilateral trade is based on the assumption of product heterogeneity, where domestic and foreign goods are distinguished by country of origin (Armington, 1969). This so-called Armington assumption provides a tractable solution to various problems associated with the standard neoclassical (Heckscher-Ohlin) perspective of trade in homogeneous goods (Whalley, 1985): *(i)* it accommodates the empirical observation that a country imports and exports the same good (so-called cross-hauling); *(ii)* it avoids over-specialization implicit to trade in homogeneous goods; and *(iii)* it is consistent with trade in geographically differentiated products. The Armington composite for a traded good is a CES function of domestic production for that sector and an imported composite. The import composite, in turn, is a CES function of production from all other countries. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO₂ emissions are linked in fixed proportions to the use of fossil fuels, with CO₂ coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of CO₂ emissions in production and consumption are implemented through exogenous emission constraints (such as the EU ETS as a cap-and-trade system) or CO₂ taxes. CO₂ emission abatement then takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).

4.1.2 Data and model parametrization

For model parameterization we follow the standard calibration procedure in applied general equilibrium analysis. The base-year input-output data together with exogenous elasticities determine the free parameters (value shares) of the cost and expenditure functions such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents. We use most recent data from the global macroeconomic balances as published by the Joint Research Centre (JRC) of the EU Commission (Keramidas, Tchung-Ming, Diaz-Vazquez, Weitzel, Vandyck, Després, Schmitz, Rey Los Santos, Wojtowicz, Schade, et al., 2018; Rey Los Santos, Wojtowicz, Tamba, Vandyck, Weitzel, Saveyn, and Temursho, 2018). The JRC data includes detailed macroeconomic accounts on production, consumption, and bilateral trade together with information on physical energy flows and CO₂ emissions for 40 regions and 31 sectors covering the world economy. The electricity sector in the JRC dataset is decomposed by region into 11 discrete generation technologies and a residual transmission and distribution sector.

Beyond the explicit information on discrete power technologies, another appealing feature of the JRC dataset is that it includes official baseline projections of future economic activities and energy use in five-year intervals until 2050. We can readily use these projected input-output tables and bilateral trade flows for our model calibration, thereby establishing a baseline scenario in 2030 as the target year against which we measure the implications of policy counterfactuals such as unilateral emissions

pricing.

The JRC dataset can be flexibly aggregated across sectors and regions to reflect specific requirements of the policy issue under investigation. For our analysis, we keep all the different primary and secondary energy carriers in the original dataset: Coal, Crude Oil, Natural Gas, Refined Oil, and Electricity. This disaggregation is essential in order to distinguish energy goods by CO₂ intensity and the degree of substitutability. In addition, we include a composite of emission-intensive and trade-exposed (EITE) industries covered by the EU ETS (i.e., Chemical Products, Non-Metallic Minerals, Iron & Steel, Non-Ferrous Metals, and Air Transport). The rest of other industries and services which — beyond final consumption — constitute the non-ETS segments of the economy are represented by an aggregate commodity. We maintain the detailed description of electricity supply provided in the JRC dataset with its explicit representation of discrete power technologies that are central to CO₂ emission reduction both in the ETS as well as the non-ETS sectors of the economy.

The regional coverage in the dataset used for model simulations reflects our focus on unilateral pricing initiatives of non-ETS emissions by EU Member States. The EU effort sharing regulation (ESR) specifies different GHG emission targets for the individual member states (Regulation (EU) 2018/842, Annex I). We sort countries according to the stringency of emission reduction targets under the ESR. At the upper end, we keep Germany, France, and the United Kingdom as individual countries because they are the largest European economies covered by the EU ETS and have expressed ambitions for stringent CO₂ emissions reduction of their non-ETS emissions. At the other end, we keep Poland as a politically important and coal-based country which is reluctant to adopt larger CO₂ emission cuts. All other EU countries are attributed to three regional aggregates: a composite region labeled R35 which comprises EU countries with high ambition targets (>35%), a composite region labeled R25 covering EU countries with moderate targets between 25- 35%, and a residual composite labeled EEC that mainly comprises the Eastern European and some smaller countries assuming that this group is unwilling to raise its reduction target for the non-ETS sector. For the sake of compactness, we limit the explicit representation of the remainder of the global economy through a composite region Rest of the World. Table 1 provides an overview of the sectors (incl. power technologies) and regions that are represented in our model.

Tab. 1: Sectors and regions in the CGE model

| <i>Sectors and commodities</i> | <i>Countries and regions</i> |
|--|---|
| <i>Primary energy sectors</i> | <i>Explicit European countries</i> |
| Coal | Germany |
| Crude Oil | United Kingdom |
| Natural Gas | France |
| <i>Emission-intensive and trade-exposed sectors</i> ¹ | Poland |
| EITE composite ² | EU composite region |
| <i>Electricity generation and distribution</i> ¹ | R35 (high targets >35%) ³ |
| Coal-fired | R25 (moderate targets >25% and <35%) ⁴ |
| Oil-fired | REU ⁵ |
| Wind power | <i>Non-EU countries/regions</i> |
| Photovoltaics | Rest of the World |
| Transmission and distribution | |
| <i>Rest of industry</i> | |
| Rest of industry and services | |

¹Regulated by the EU ETS (except for power transmission and distribution)

²EITE includes: Chemical Products, Non-Metallic Minerals, Iron and Steel, Non-Ferrous Metals, Refined Oil, Paper Products and Publishing, Air Transport

³R35 includes: Denmark, Finland, Sweden, Luxembourg, Netherlands, Austria

⁴R25 includes: Belgium, Spain, Ireland, Italy

⁵REU includes: Bulgaria, Estonia, Croatia, Latvia, Lithuania, Romania, Slovakia, Slovenia, Czech Republic, Hungary, Greece, Malta, Portugal, Cyprus

The responses of agents to price changes are determined by a set of exogenous elasticities taken from the econometric literature. Elasticities in international trade (Armington elasticities) and substitution possibilities in production (between primary factor inputs) are directly provided by the JRC database. The elasticities of substitution in fossil fuel production are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham, Thorpe, and Hogan, 1999; Krichene, 2002; Ringlund, Rosendahl, and Skjerpen, 2008)). Supply elasticities for power generation lean on estimates taken from the EPPA model (Chen, Jensen, Kirkerud, and Bolkesjø, 2021).

Regarding supply elasticities for power-to-X technologies, we are not aware of empirical studies reflecting the fact that such technologies are not yet profitable. In our numerical implementation, we therefore have to assume the cost gap for breaking even as well as the speed of market penetration (i.e. technology-specific supply elasticities) when fossil fuel prices (due to carbon pricing) increase and sector coupling becomes positive. As such information is highly uncertain, we perform sensitivity analysis with lower and higher values for the cost and elasticity assumptions of our central scenario.

4.2 Policy scenario

In our central policy scenarios, we focus on 2030 as the milestone for EU climate policies. The benchmark situation in 2030 as captured by the JRC projections already incorporates the EU’s initial 2030 target of a 40 percent GHG emissions reduction as compared to 1990. This target aligns with the emissions reduction pledge that the EU made 2015 under the Paris Agreement, including the EU ETS with an emissions cap of 43 percent below the emissions level in 2005.

Recently, however, the EU commission has been pushing for stricter climate policies, as reflected in the European Green Deal (COM(2019) 640 final) and the “Fit for 55 package” of law reform proposals (COM(2021) 551 final). This package aims to raise the reduction target for 2030 from 40 to 55 percent, which is equivalent to a reduction of EU emissions under the original 2030 target by an additional 25 percent. We adopt this for our central scenario and allocate the resulting reduction obligations to the different sectors and countries as follows.

Tab. 2: Comparison of results on emissions from analytical and numerical model

| change of ... | | analytical model | CGE model |
|-----------------|----------------|------------------------|-----------|
| emissions price | non-ETS sector | $\Delta\tau_{COA} > 0$ | 125.2€/t |
| | ETS sector | $\Delta\nu > 0$ | 12€/t |
| emissions in | COA | $\Delta e_{xA} < 0$ | −32.8% |
| non-ETS sector | NCOA | $\Delta e_{xB} > 0$ | 0.7% |
| emissions in | COA | $\Delta e_{yA} > 0$ | 3.1% |
| ETS sector | NCOA | $\Delta e_{yB} < 0$ | −6.9% |
| total emissions | COA | $\Delta e_A?$ | −18.9% |
| | NCOA | $\Delta e_B?$ | −3.2% |
| | COA + NCOA | $\Delta e < 0$ | −14.9% |

In the ETS sector, there exists a common cap for all member states and we assume that agreement can be reached to strengthen this cap by the required 25 percent. By contrast, for the non-ETS sector, the effort sharing regulation (ESR) specifies different GHG emission targets for the individual member states. We sort countries into two groups according to whether their reduction target under the ESR is below or above 25 percent (Regulation (EU) 2018/842, Annex I). We take these numbers as reflecting lower ambitions of the first group (called “NCOA”) that mainly comprises the Eastern European and some smaller countries, and assume that this group is unwilling to raise its reduction target for the non-ETS sector. For the second group (called “COA”), by contrast, we assume that they are willing to “unilaterally” raise their ESR reduction targets such that *EU-wide* emissions in the non-ETS sector are reduced by the additional 25 percent that are required to implement the new 55 percent target. To achieve this, each of the more ambitious countries will raise its original 2030 ESR reduction target by an additional 32 percent. Moreover, we assume that the group of COA-countries establishes a new emissions trading system for the non-ETS sector, for which the strengthened ESR reduction obligations serve as the initial permit allocation. Obviously, the resulting permit price has the same effects on these countries’ abatement incentives as the unilateral emissions tax that we used in the theoretical analysis. The following table summarizes reduction targets and other key parameters in our main scenario.

Remember that the main purpose of our numerical analysis is not an evaluation of proposals to implement the 55 percent target, such as the EU Commission’s “Fit for 55 package” (COM(2021) 551 final). Instead, in accordance with the theoretical analysis we want to investigate how unilateral action in the non-ETS sector by a coalition of ambitious countries affects via sector coupling and the ETS the other group of less ambitious countries.

5 Comparison of results from analytical and numerical model

Tables 2 and 3 compare (i) the signs of the comparative statics of unilateral emission reduction policies in the non-ETS sector that have been derived in the analytical model (Propositions 1 and 2) with (ii) the corresponding quantitative effects in the CGE model. Accordingly, for the CGE model we use the situation after emissions in the ETS sector have been reduced by 55 percent as the reference point. The numerical model is substantially more complex than the analytical one and includes several additional effects such as trade in electricity. Nevertheless, all of the listed changes are consistent with the results from the analytical model. Most importantly, the unilateral emission reductions of COA in the non-ETS sector reduce total emissions in NCOA by −3.2 percent; hence we have negative leakage.

The consistency of the results from the analytical and the numerical model indicates that the

Tab. 3: Comparison of further results from analytical and numerical model

| change of ... | | analytical model | CGE model |
|-------------------------------|------------|---------------------|-----------|
| electricity price (P_user) | DE | $\Delta p_{yA} > 0$ | 2.5% |
| | EEC | $\Delta p_{yB} > 0$ | 2% |
| electricity | fossils | $\Delta y_{dA} > 0$ | 21.46% |
| generation COA | renewables | $\Delta y_{cA} > 0$ | 5.2% |
| electricity | fossils | $\Delta y_{dB} < 0$ | -9.8% |
| generation NCOA | renewables | $\Delta y_{cB} > 0$ | 3.2% |

mechanisms which we have discussed in Section 3 do actually play a dominating role. We now investigate this further. Raising the original 2030 ESR reduction target by an additional 32 percent leads to a permit price of 125.2€ per ton of CO₂ in the non-ETS sector of COA-countries. This makes fossil technologies in this sector less attractive and leads, in particular, to electrification of mobility and heating. This requires more electricity generation, which comes from fossil and renewable technologies, and results in a higher electricity price. Moreover, the additional fossil electricity generation leads to a higher permit demand in COA countries, which raises the permit price in the ETS-sector (see Table 2). This makes fossil electricity generation in NCOA countries more expensive so that it falls. Given lower supply, the electricity price rises, which is further reinforced by higher demand for electricity imports to COA – an effect that we have ignored in the analytical model. Finally, in contrast to COA the higher electricity price in NCOA is not accompanied by an emissions price in the non-ETS sector. Therefore, the higher electricity price hampers electrification of the non-ETS sector.

6 Concluding remarks

The transition towards a zero-emission economy until mid of the century hinges on the possibility to run all energy-related processes from electricity produced via carbon-free renewable energy sources. All energy consuming sectors — buildings (heating and cooling), transport, and industry — will be linked and integrated with the power producing sector. Such (so-called) sector coupling is based on direct and indirect electrification using Power-to-X technologies which decouple power from the electricity sector for use in other sectors.

In the case of direct electrification, fossil fuels are directly replaced by electricity. Examples include the replacement of an oil-fired heating system with an electric heat pump (known as power-to-heat) or the use of electric motors in vehicles (power-to-mobility) instead of gasoline or diesel engines. Indirect electrification refers to the conversion of electric power into another non-electric energy carrier, such as the use of electrolysis to produce hydrogen or methane (power-to-gas), which can then be used to fuel motor vehicles or steel production (green hydrogen).

In a nutshell, sector coupling will be of utmost importance to achieve a zero-emission economy. In this article, we have analyzed its implications in the presence of an ETS, where one group of countries implements a unilateral emissions tax in the non-ETS sector that needs to be electrified. We have shown that this policy leads to negative leakage that results from the combined effects of linkage across sectors via electrification and linkage across countries via the ETS. Thus, taxing fossil fuel based mobility or heating — as some EU countries have implemented unilaterally — has spillover effects that maybe considered as desirable: via a higher permit price it raises the costs and, thus, reduces the output of the most CO₂ intensive electricity generation technologies, especially coal. Moreover, this obtains in all countries that are covered under the ETS, including those that are most reluctant to implement ambitious reduction policies. This contrast sharply with unilateral action in the ETS sector that is hampered by the given permit endowment unless allowances are cancelled.

Whereas we have analyzed a tax in the non-ETS sector, unilateral policies that support the electricity-based technology in the non-ETS sector — such as the subsidization of electric vehicles (EVs) — should have similar effects. To put it somewhat pointedly, this means that switching to EVs does not only reduce emissions in the mobility sector. Via the resulting higher permit prices it also contributes to replacing coal by other, less CO₂ intensive production technologies — and this effect is the strongest in those countries that still rely heavily in coal.

There are several directions in which the analysis could be extended. One issue is a more detailed analysis of the factors that determine the effects of sector coupling, especially within the CGE model. This also includes a much more profound sensitivity analysis than in the current version. Moreover, our analysis has focused on emission effects and how they are distributed across sectors and countries. It would be interesting to also see how the interlinkages via sector coupling and the ETS spread the welfare effects of unilateral policies in the non-ETS sector across countries, and to what extent emission reduction costs are shifted to other countries.

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A Appendix

A.1 Proof of Proposition 1

From the first-order conditions of firms (Eqs. 5 to 8) and consumers (Eqs. 9 and 10) it follows immediately that marginal utilities are equal to marginal production for all sectors and technologies in $i \in N$:

$$\frac{\partial u_i(y_i)}{\partial y_i} = C'_{di}(y_{di}) + \nu \alpha_y, \quad (14)$$

$$\frac{\partial u_i(y_i)}{\partial y_i} = C'_{ci}(y_{ci}), \quad (15)$$

$$\frac{\partial u_i(x_i)}{\partial x_i} = C'_{di}(x_{di}) + \tau_i \alpha_x, \quad (16)$$

$$\frac{\partial u_i(x_i)}{\partial x_i} = C'_{ci}(x_{ci}) + \beta C'_{ci}(y_{ci}), \quad (17)$$

where we have used $\beta C'_{ci}(y_{ci}) = \beta p_{yi}$ (from Eq. 6) to derive the right-hand side of the last line. Intuitively, marginal costs of clean mobility include marginal electricity costs.

Remember that $\Delta y_i := \tilde{y}_i - y_i$ denotes the change in output due to the unilateral tax. We also use this Δ -notation for utility and cost functions. In particular, let $u'(\tilde{y}_i)$ and $u'(y_i)$ denote the marginal utilities at the consumption values with and without the unilateral tax, respectively. Then $\Delta u'(y_i) := u'(\tilde{y}_i) - u'(y_i)$ is the change in marginal utilities due to the tax.

Note that the first-order conditions (14) to (17) must hold in all situations, i.e. independent of whether a unilateral tax is imposed or not. For each of these four expressions, we subtract the respective first-order conditions with and without the unilateral tax, yielding³

$$\Delta u'_i(y_i) = \Delta C'_{di}(y_{di}) + \alpha_y \Delta \nu, \quad (18)$$

$$\Delta u'_i(y_i) = \Delta C'_{ci}(y_{ci}), \quad (19)$$

$$\Delta u'_i(x_i) = \Delta C'_{di}(x_{di}) + \alpha_x \Delta \tau_i, \quad (20)$$

$$\Delta u'_i(x_i) = \Delta C'_{ci}(x_{ci}) + \beta \Delta C'_{ci}(y_{ci}), \quad (21)$$

³ For example, let

$$\begin{aligned} u'_i(\tilde{y}_i) &= C'_{di}(\tilde{y}_{di}) + \tilde{\nu} \alpha_y \\ u'_i(y_i) &= C'_{di}(y_{di}) + \nu \alpha_y \end{aligned}$$

be the expressions of equilibrium condition (14) with and without the tax. Subtraction yields (18), where $\Delta u'_i(y_i) := u'_i(\tilde{y}_i) - u'_i(y_i)$ and so on.

The same can be done for the market clearing conditions, yielding

$$\Delta x_i = \Delta x_{di} + \Delta x_{ci} \text{ and } \Delta y_i = \Delta y_{di} + \Delta y_{ci} - \beta \Delta x_{ci}, i \in N. \quad (22)$$

Note that $\Delta y_{dA} := \tilde{y}_{dA} - y_{dA} > 0$ implies $\Delta C'_{dA}(y_{dA}) := C'_{dA}(\tilde{y}_{dA}) - C'_{dA}(y_{dA}) < 0$ by convexity of the cost functions. It is straightforward to see that this argument can be generalized to all technologies in both countries so that the difference in marginal abatement costs and the difference in corresponding output values always have the same sign. Formally,

$$\Delta y_{ki} \gtrless 0 \iff \Delta C'_{ki}(y_{ki}) \gtrless 0 \text{ and } \Delta x_{ki} \gtrless 0 \iff \Delta C'_{ki}(x_{ki}) \gtrless 0, k = d, c; i \in N. \quad (23)$$

Similarly, due to concavity of the utility functions, the difference in marginal utilities and the difference in corresponding consumption values always have the opposite sign, i.e.

$$\Delta y_i \gtrless 0 \iff \Delta u'_i(y_i) \lessgtr 0 \text{ and } \Delta x_i \gtrless 0 \iff \Delta u'_i(x_i) \lessgtr 0, i \in N. \quad (24)$$

We can now prove the statements in the proposition and begin with $\Delta y_{dA} > 0$. By contradiction, suppose $\Delta y_{dA} \leq 0$. From the exogenously given permit allocation in the ETS sector this immediately implies that there must be at least one other country, denoted B , for which $\Delta y_{dB} \geq 0$. Note that either $\Delta \nu > 0$ or $\Delta \nu \leq 0$. Starting with the first case, from (18) we have $\Delta u'_B(y_B) > 0$. This in turn implies that $\Delta y_B = \Delta y_{dB} + \Delta y_{cB} - \beta \Delta x_{cB} < 0$ (from 24 and 22) as well as $\Delta y_{cB} > 0$ (from 19 and 23). Using this and the assumption $\Delta y_{dB} \geq 0$, we have $\Delta x_{cB} > 0$. Moreover, from (21), we obtain $\Delta u'(x_B) > 0$ so that $\Delta x_B = \Delta x_{dB} + \Delta x_{cB} < 0$, which requires $\Delta x_{dB} < 0$. However, using $\Delta \tau_B = 0$ and (20), $\Delta u'(x_B) > 0$ also implies that $\Delta C'_{dB}(x_{dB}) > 0 \implies \Delta x_{dB} > 0$. Hence we have a contradiction.

Turning to the second case $\Delta \nu \leq 0$, the initial assumption $\Delta y_{dA} \leq 0$ implies $\Delta u'_A(y_A) \leq 0$. Therefore, $\Delta y_A = \Delta y_{dA} + \Delta y_{cA} - \beta \Delta x_{cA} \geq 0$ and $\Delta y_{cA} \leq 0$ from (24), (22) and (19). It follows that $\Delta x_{cA} \leq 0$. Using (21), we obtain $\Delta u'_A(x_A) \leq 0$ so that given the policy assumption $\Delta \tau_A > 0$, condition (20) can only be satisfied if $\Delta C'_{dA}(x_{dA}) < 0 \implies \Delta x_{dA} < 0$. However, $\Delta u'_A(x_A) \leq 0$ also implies that $\Delta x_A = \Delta x_{dA} + \Delta x_{cA} \geq 0$ which cannot be satisfied for the above results that $\Delta x_{cA} \leq 0$ and $\Delta x_{dA} < 0$. Hence we have again a contradiction and conclude that $\Delta y_{dA} > 0$.

Next, by contradiction to statement (a), suppose that $\Delta \nu \leq 0$. As we have already shown that $\Delta y_{dA} > 0$, there must be at least one other country, denoted B , for which $\Delta y_{dB} < 0$. Hence $\Delta C'_{dB}(y_{dB}) < 0$ and it follows from (18) that $\Delta u'(y_B) < 0$.⁴ This in turn implies $\Delta y_B = \Delta y_{dB} + \Delta y_{cB} - \beta \Delta x_{cB} > 0$ (from 24 and 22) as well as $\Delta y_{cB} < 0$ (from 19 and 23). Using this and $\Delta y_{dB} < 0$, we have $\Delta x_{cB} < 0$. Moreover, from (21), we obtain $\Delta u'(x_B) < 0$ so that $\Delta x_B = \Delta x_{dB} + \Delta x_{cB} > 0$, which requires $\Delta x_{dB} > 0 \implies \Delta C'_{dB}(x_{dB}) > 0$. Together with $\Delta \tau_B \geq 0$, (20) then implies $\Delta u'(x_B) \geq 0$, which yields a contradiction.

We conclude that $\Delta \nu > 0$. Moreover, in the paragraph after expression (24), we have already shown for $\Delta \nu > 0$ there can be no other country B for which $\Delta y_{dB} \geq 0$. Therefore, the higher permit price implies that fossil electricity production falls in all countries other than the one that undertakes unilateral action, i.e., $\Delta y_{di} < 0$ for all countries $i \neq A$.

Using $\Delta \nu > 0$ and $\Delta y_{dA} > 0 \implies \Delta C'_{dA}(y_{dA}) > 0$, it follows from (18) that $\Delta u'_A(y_A) > 0$. Hence, $\Delta y_{cA} > 0$ (from 19 and 23) and $\Delta y_A = \Delta y_{dA} + \Delta y_{cA} - \beta \Delta x_{cA} < 0$, which can only be satisfied if $\Delta x_{cA} > 0$. Using this, $\Delta y_{cA} > 0$ and (23), we conclude from (21) that $\Delta u'_A(x_A) > 0 \implies \Delta x_A = \Delta x_{dA} + \Delta x_{cA} < 0$. This requires $\Delta x_{dA} < 0$.

We now turn to the other countries $i \neq A$ that do not undertake unilateral action and index them by j . By contradiction, suppose that $\Delta y_j \geq 0$. Hence $\Delta u'(y_j) \leq 0$ so that from (19) $\Delta y_{cj} \leq 0$. Using this and $\Delta y_{dj} < 0$, $\Delta y_j = \Delta y_{dj} + \Delta y_{cj} - \beta \Delta x_{cj} \geq 0$ requires $\Delta x_{cj} < 0$. Hence from (21)

⁴ As mentioned before Proposition 1, much of the literature uses total differentiation. To see that our proof could easily be revised to follow this method, consider the following example: Total differentiation of (14) yields $u''(y_i)dy_i = C''_{di}(y_{di})dy_{di} + \alpha d\nu$. For $d\nu < 0$ and $dy_{dB} < 0$ it follows immediately from $C''_{di}(y_{di}) > 0$ and $u''(y_i) < 0$ that $dy_B = dy_{dB} + dy_{cB} - \beta dx_{cB} > 0$.

one gets $\Delta u'(x_j) < 0$ so that $x_j > 0$ and from (20) $\Delta x_{dj} < 0$. Together with $\Delta x_{cj} < 0$ we get $\Delta x_j = \Delta x_{cj} + \Delta x_{dj} < 0$, a contradiction. We conclude that $\Delta y_j < 0 \implies \Delta u'(y_j) > 0$. Using this, $\Delta y_{cj} > 0$ follows from (19).

Next, consider the non-ETS sector and suppose by contradiction that $\Delta x_j \geq 0 \implies \Delta u'(x_j) \leq 0$. Then from (20) $\Delta x_{dj} \leq 0$, and from (21) $\Delta x_{cj} < 0$ since we have already shown that $\Delta y_{cj} > 0$. Therefore, $\Delta x_j = \Delta x_{cj} + \Delta x_{dj} < 0$, a contradiction. We conclude that $\Delta x_j < 0 \implies \Delta u'(x_j) > 0$. For $\Delta \tau_j = 0$ this implies $\Delta x_{dj} > 0$ (from 20) so that $\Delta x_j = \Delta x_{cj} + \Delta x_{dj} < 0$ requires $\Delta x_{cj} < 0$.

Turning to prices, subtraction of consumers' respective first-order conditions (9) and (10) with and without the unilateral tax yields for all $i \in N$:

$$\Delta u'_i(y_i) = \Delta p_{yi}, \quad (25)$$

$$\Delta u'_i(x_i) = \Delta p_{xi}. \quad (26)$$

Using this, Eqs. (24) and the above results that consumption falls in both sectors ($\Delta x_i < 0, \Delta y_i < 0$), it follows immediately that the corresponding prices rise in both sectors; as one would expect.

A.2 Proof of Proposition 2

We only need to prove statement (b), because (a) has already been shown in the paragraphs before the proposition. Given the cap in the electricity sector, $\sum_{i \in N} \Delta y_{di} = 0$ so that the change in overall emissions is $\Delta e = \alpha_x \sum_{i \in N} \Delta x_{di}$. Summation of the second expression in (22) over all countries, using $\sum_{i \in N} \Delta y_{di} = 0$, and rearranging yields $\beta \sum_{i \in N} \Delta x_{ci} = \sum_{i \in N} \Delta y_{ci} - \sum_{i \in N} \Delta y_i > 0$, where the greater-than sign follows from the signs Δy_{ci} and Δy_i in Proposition 1. Hence $\sum_{i \in N} \Delta x_{ci} > 0$. Moreover, from Proposition 1, $\Delta x_i = \Delta x_{di} + \Delta x_{ci} < 0$ so that $\Delta x_{di} < -\Delta x_{ci}$ for all $i \in N$. Adding up this expression yields $\sum_{i \in N} \Delta x_{di} < -\sum_{i \in N} \Delta x_{ci}$. As we have already shown that the right-hand side is strictly negative, the remaining claims $\sum_{i \in N} \Delta x_{di} < 0$ and $\Delta e = \alpha_x \sum_{i \in N} \Delta x_{di} < 0$ follow immediately.

A. Computable general equilibrium model

Our model is formulated as a mixed complementarity problem. The competitive equilibrium is characterized by three classes of conditions: zero profit conditions for all economic activities, market clearance for all markets, and income balance for all agents. We use the notation Π_{ir}^u to denote the profit function of sector i in region r where u denotes the associated production activity. Indices i and j index commodities, including a composite public good G and a composite investment good I . Indices r and s index regions. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. The notations used are summarized in Tables 1-6.

A.1. Zero profit conditions

1. Production of goods except fossil fuels ($i \notin FF$)

$$\Pi_{ir}^Y = \left[\theta_{ir}^D p_{ir}^{D^{1-\eta_{ir}}} + (1 - \theta_{ir}^D) p_{ir}^{EX^{1-\eta_{ir}}} \right]^{1-\eta_{ir}} - p_{ir}^{KLEM} \leq 0$$

2. Sector- and region-specific aggregate of value added, labor, energy, and non-energy inputs ($i \notin FF$)

$$\begin{aligned} \Pi_{ir}^{KLEM} = p_{ir}^{KLEM} - & \left[\theta_{ir}^{KLE} \left[\theta_{ir}^{KL} p_{ir}^{KL^{1-\sigma_{ir}^{KLE}}} \right. \right. \\ & \left. \left. + (1 - \theta_{ir}^{KL}) p_{ir}^{E^{1-\sigma_{ir}^{KLE}}} \right]^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{KLE}}} \right. \\ & \left. + (1 - \theta_{ir}^{KLE}) \left(\sum_{j \notin EG} \theta_{jir}^{NE} p_{jr}^A \right)^{\frac{1-\sigma_{ir}^{KLEM}}{1-\sigma_{ir}^{NE}}} \right]^{\frac{1}{1-\sigma_{ir}^{KLEM}}} \leq 0 \end{aligned}$$

3. Sector- and region-specific value added aggregate ($i \notin FF$)

$$\Pi_{ir}^{KL} = p_{ir}^{KL} - \left[\theta_{ir}^K w_r^{1-\sigma_{ir}^{KL}} + (1 - \theta_{ir}^K) v_r^{1-\sigma_{ir}^{KL}} \right]^{\frac{1}{1-\sigma_{ir}^{KL}}} \leq 0$$

4. Sector-specific energy aggregate ($i \notin FF$)

$$\begin{aligned} \Pi_{ir}^E = p_{ir}^E - & \left\{ \theta_{ir}^{ELE} p_{ELE,r}^{A^{1-\sigma_{ir}^E}} + \theta_{ir}^{COA} (p_{COA,r}^A + p_r^{CO_2} a_{COA}^{CO_2})^{1-\sigma_{ir}^E} \right. \\ & \left. + \theta_{ir}^{GAS} (p_{GAS,r}^A + p_r^{CO_2} a_{GAS}^{CO_2})^{1-\sigma_{ir}^E} + \theta_{ir}^{OIL} (p_{OIL,r}^A + p_r^{CO_2} a_{OIL}^{CO_2})^{1-\sigma_{ir}^E} \right\} \leq 0 \end{aligned}$$

5. Production of fossil fuels ($i \in FF$)

$$\Pi_{ir}^Y = \left[\theta_{ir}^D p_{ir}^{D^{1-\eta_{ir}}} + (1 - \theta_{ir}^D) p_{ir}^{EX^{1-\eta_{ir}}} \right]^{1-\eta_{ir}} - \left[\theta_{ir}^Q q_{ir}^{1-\sigma_i^Q} + (1 - \theta_{ir}^Q) \left(\theta_{Lir}^{FF} w_r \theta_{Kir}^{FF} v_r + \sum_j \theta_{jir} (p_{ir}^A + p_r^{CO_2} a_j^{CO_2}) \right)^{1-\sigma_i^Q} \right]^{\frac{1}{1-\sigma_i^Q}} \leq 0$$

6. Armington aggregate ($i \notin FF$)

$$\Pi_{ir}^A = p_{ir}^A - \left(\theta_{ir}^A p_{ir}^{D^{1-\sigma_{ir}^A}} + (1 - \theta_{ir}^A) p_{ir}^{M^{1-\sigma_{ir}^A}} \right)^{\frac{1}{1-\sigma_{ir}^A}} \leq 0$$

7. Aggregate imports across regions

$$\Pi_{ir}^M = p_{ir}^M - \left(\sum_s \theta_{isr}^M p_{is}^{EX^{1-\sigma_{ir}^M}} \right)^{\frac{1}{1-\sigma_{ir}^M}} \leq 0$$

A.2. Market clearance conditions

8. Labor

$$\bar{L}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r}$$

9. Capital

$$\bar{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

10. Natural resources ($i \in FF$)

$$\bar{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}}$$

11. Output

$$Y_{ir} \geq \sum_j A_{jr} \frac{\Pi_{jr}^A}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}$$

12. Armington aggregate

$$A_{ir} \geq \sum_j Y_{jr} \frac{\Pi_{jr}^Y}{\partial p_{ir}} + C_r \frac{\partial \Pi_r^C}{\partial p_{ir}^A}$$

13. Import aggregate

$$M_{ir} \geq A_{ir} \frac{\Pi_{ir}^A}{\partial p_{ir}^M}$$

14. Public consumption

$$Y_{Gr} \geq \bar{G}_r$$

15. Investment

$$Y_{Ir} \geq \bar{I}_r$$

16. CO₂ emissions

$$\bar{CO2}_r \geq \sum_i A_{ir} a_i^{CO_2}$$

A.3. Income balance

17. Income-expenditure balance

$$C_r p_r^C = w_r \bar{L}_r + v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} + p_{Ir} \bar{Y}_{Ir} + p_{Gr} \bar{Y}_{Gr} + \bar{B}_r + p_r^{CO_2} \bar{CO2}_r$$

Table 1: Sets and indexes

| | |
|--------|---|
| i, j | Indexes for sectors and goods |
| r, s | Indexes for regions |
| EG | All energy goods: Coal, crude oil, refined oil, gas and electricity |
| FF | Primary fossil fuels: Coal, crude oil and gas |

Table 2: Activity variables

| | |
|----------|---|
| Y_{ir} | Production in sector i and region r |
| E_{ir} | Aggregate energy input in sector i and region r |
| M_{ir} | Aggregate imports of good i and region r |
| A_{ir} | Armington aggregate for good i in region r |
| C_r | Aggregate household consumption in region r |

Table 3: Price variables

| | |
|-----------------|--|
| p_{ir}^D | Domestic supply price of good i produced in region r |
| p_{ir}^{EX} | Export supply price of good i produced in region r |
| p_{ir}^{KLEM} | Price of aggregate value-added, energy and non-energy in sector i and region r |
| p_{ir}^{KL} | Price of aggregate value-added in sector i and region r |
| p_{ir}^E | Price of aggregate energy in sector i and region r |
| p_{ir}^M | Import price aggregate for good i imported to region r |
| p_{ir}^A | Price of Armington good i in region r |
| p_r^C | Price of aggregate household consumption in region r |
| w_r | Wage rate in region r |
| v_r | Price of capital services in region r |
| q_{ir} | Rent to natural resources in region r ($i \in FF$) |
| $p_r^{CO_2}$ | CO ₂ emissions price in region r |

Table 4: Cost shares

| | |
|----------------------|--|
| θ_{ir}^D | Share of domestic supply in sector i and region r |
| θ_{ir}^{KLEM} | Cost share of $KLEM$ aggregate in sector i and region r |
| θ_{ir}^{KLE} | Cost share of value-added and energy in the KLE aggregate in sector i and region r |
| θ_{ir}^{KL} | Cost share of value-added in the KLE aggregate in sector i and region r |
| θ_{ir}^K | Cost share of capital in value-added composite of sector i and region r |
| θ_{jir}^{NE} | Cost share of non-energy input j in the non-energy aggregate in sector i and region r |
| θ_{ir}^E | Cost share of energy composite in the KLE aggregate in sector i and region r ($i \notin FF$) |
| θ_{ir}^Q | Cost share of natural resources in sector i and region r ($i \in FF$) |
| θ_{Tir} | Cost share of good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in sector i and region r ($i \in FF$) |
| θ_{ir}^{ELE} | Cost share of electricity in energy composite in sector i in region r ($i \notin FF$) |
| θ_{ir}^{FF} | Cost share of fossil fuel FF in energy composite in sector i in region r ($i \notin FF$) |
| θ_{isr}^M | Cost share of imports of good i from region s to region r |
| θ_{ir}^A | Cost share of domestic variety in Armington good i of region r |

Table 5: Elasticities

| | |
|----------------------|---|
| η_r | Transformation between domestic and export supply |
| σ_{ir}^{KLEM} | Substitution between KLE aggregate and material inputs |
| σ_{ir}^{KLE} | Substitution between energy and value-added in production |
| σ_{ir}^{KL} | Substitution between labor and capital in value-added composite |
| σ_{jir}^{NE} | Substitution between materials |
| σ_{ir}^Q | Substitution between natural resources and other inputs in fossil fuel production calibrated to exogenous supply elasticities |
| σ_{ir}^{ELE} | Substitution between electricity and the fossil fuel aggregate |
| σ_{ir}^A | Substitution between the import aggregate and the domestic input |
| σ_{ir}^M | Substitution between imports from different regions |

Table 6: Endowments and emissions coefficients

| | |
|----------------|---|
| \bar{L}_r | Aggregate labor endowment in region r |
| \bar{K}_r | Aggregate capital endowment in region r |
| \bar{Q}_{ir} | Endowment of natural resource i in region r |
| \bar{G}_r | Public good provision in region r |
| \bar{I}_r | Investment demand in region r |
| \bar{B}_r | Balance of payment deficit or surplus in region r |
| $\bar{CO2}_r$ | CO ₂ emission constraint for region r |
| a_i^{CO2} | CO ₂ emissions coefficient for fossil fuel i |