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The Reverse Waterbed Effect of Sector Coupling — Unilateral Climate Policies and Multilateral Emissions Trading

Abstract

It is widely acknowledged that the transition towards a zero-emissions economy requires electrification of energy-related processes across all sectors of the economy — so-called sector coupling. In our analysis we consider countries whose electricity sectors are regulated by a multilateral emissions trading system (ETS). We examine the implications of a unilateral CO_2 tax by a group of countries on emissions in their transport and buildings sectors. The tax induces a switch to electricity-based technologies (e.g., electric vehicles and heat pumps), thus raising the demand for emission allowances and their price in the electricity sector. This induces emission reductions in the electricity sectors of the other countries covered under the ETS; hence we have a "reverse waterbed effect". CO_2-intensive electricity generation technologies, especially coal, are most affected by this and their output falls as a result of sector coupling. Subsidies for electricity-based technologies in the transport and buildings sectors have similar effects, and the main insights still hold if these sectors are governed by a separate ETS, as it is planned for the EU. We examine this in a stylized analytical model and use a computable general equilibrium model calibrated to data for the EU to quantify the effects. Moreover, for the case of a second ETS, our numerical results suggest that the unilateral cancellation of emission allowances in the power sector leads to substantially higher welfare losses than doing so in the transport and buildings sectors.

JEL-Codes: H230, D580, Q540, Q380.

Keywords: sector coupling, unilateral action, overlapping regulation, ETS, reverse waterbed effect.

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1 Introduction

The transition towards a zero-emissions economy hinges on the replacement of all fossil fuels by energy from CO_2-free renewable energy sources. This requires the coupling of the power sector to the other energy consuming (OEC) sectors, which is often referred to as sector coupling. Examples for direct electrification include the switch from oil- or gas-fired heating systems to electric heat pumps (power-to-heat) and from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs) (power-to-transport). 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).

In this paper we analyse how sector coupling affects the assessment of unilateral climate policies which overlap with a multilateral emissions trading system (ETS) that covers power generation. This setting reflects that we are in a second-best world where (*i*) trans-regional emissions reduction policies suffer from the reluctance of the least ambitious members and (*ii*) calls for uniform CO_2 pricing across all sectors of the economy have failed so far. The topic is of growing importance as the number of emissions trading systems has increased substantially (World Bank, 2022) and sector coupling is becoming pivotal for the transition towards a zero-emissions economy.

The literature has focused on overlapping regulations *within* the ETS sector which typically includes power generation as the most important source of CO_2 emissions. Prime examples of unilateral regulations undertaken by environmentally more ambitious countries are the subsidization of renewable energies in power generation and the phasing out of coal-fired power plants. These policies are not only a potential source of excess cost, but may also be ineffective in achieving their objectives due to the so-called waterbed effect: For a given ETS budget of allowances, unilateral emission reductions mainly divert emissions to the other ETS countries (or regions). Metaphorically speaking, the reduced emissions pop up at the other side of the waterbed (see, e.g., Eichner and Pethig, 2019).

By contrast, in this paper we analyse the economic and environmental impacts of policies in the OEC sectors. In the EU, the sectors not covered by the ETS currently account for roughly half of CO_2 emissions, mainly through fossil-fuel-based transport and heating. In our main scenario, we assume that these OEC sectors are not regulated by a cap and trade system and examine the unilateral implementation of a CO_2 tax or, alternatively, subsidies for electricity-based technologies. Obviously, these policies reduce emissions in the OEC sectors of the countries that implement them. Moreover, by fostering sector coupling they increase the demand for electricity and, thus, for emission allowances in the ETS for the power market. The resulting higher allowance price provides incentives for *all* countries to reduce emissions, including those reluctant to adopt more ambitious emissions abatement targets. Metaphorically speaking, we have a *reverse* waterbed effect as some of the emissions that result from the higher electricity demand in the unilateral action countries are taken from the other side of the waterbed.

To illustrate the policy relevance of accounting for the effects of sector coupling, consider the widespread subsidies for BEVs. It is often criticized that these contribute little to CO_2 emission reductions as long as the share of electricity production from fossil fuels is relatively large.[1] Sometimes it is then recommended to focus on improving the efficiency of internal combustion engine vehicles. However, this would only partially reduce emissions, and the effects are mainly restricted to the countries that implement this policy. By contrast, if conventional vehicles are replaced by BEVs, emissions from the former are fully avoided, whereas the cap in the ETS ensures that emissions from producing the required additional electricity cannot rise. Moreover, the allowance price rises for all countries under the ETS, with the strongest effects for the most CO_2-intensive technologies. In this

[1] As Hans-Werner Sinn has put it in The Guardian (www.theguardian.com/environment/2019/nov/25/are-electric-vehicles-really-so-climate-friendly): "Electric vehicles also emit substantial amounts of CO_2; the only difference being that the exhaust is released at the power plant". Similarly, in a recent analysis of the climate footprint of BEVs, Hung, Völler, Agez, Majeau-Bettez, and Strømman (2021, p. 8) write: "In the countries with the most carbon intensive electricity mixes, such as Poland, Serbia and North Macedonia, current BEVs in different segments present either negligible advantages or even increases in life-cycle emissions when compared to their ICEV counterparts. In such countries, electrification represents a climate disadvantage."

respect, unilateral subsidies for BEVs accelerate a coal phase-out, especially when the CO_2 emissions intensity of electricity generation is high.

In the first part of the paper, we develop a simple theoretical model to identify the main cross-sector and cross-country transmission mechanisms at play. The model comprises N countries that each have an ETS sector (electricity) and an OEC sector (transport/heating), both of which operate with a clean (renewable-electricity-based) and a dirty (fossil-fuel-based) technology. Sector coupling and the ETS create linkages between sectors and countries, respectively. If one country (or a group of countries) unilaterally taxes the dirty technology or subsidizes the clean one in the OEC sector, output shifts towards the clean technology. The resulting higher electricity demand raises the emissions allowance price in the ETS sector and, thus, the costs of the dirty technology *in all* countries covered by the ETS. For the unilaterally acting country we show that emissions fall in the OEC sector but rise in the ETS sector, whereas this pattern is reversed in the other countries.

We then examine the situation where also the OEC sector is regulated by an emissions trading system, though a separate one. This reflects the December 2022 agreement between the EU Council and Parliament to create a new, separate emissions trading system for the buildings and road transport sectors and fuels for certain other sectors.[2] We call this the ETS II, whereas the (non-extended) acronym ETS is used for the power sector; i.e., for the existing EU ETS in our numerical application. Obviously, the unilateral tax and subsidy instruments would no longer be effective due to the waterbed effect in the OEC sector. Therefore, we instead examine the unilateral cancellation of ETS II emission allowances. Also this policy induces sector coupling with feedback effects on the ETS for the power sector. However, the direct effects of allowance cancellations in the OEC sector are more symmetrically distributed between countries as they all face the same higher allowance price, in contrast to a unilateral tax or subsidy. Moreover, we compare this with the alternative of cancelling allowances in the ETS. That policy results in higher electricity prices and, therefore, negatively impacts the transition towards clean, electricity-based technologies in the OEC sector. By contrast, the cross-sectoral effects of cancelling ETS II allowances are more in line with the envisaged energy transition as they also raise the output of the clean, renewables-based technology in the other sector.

In the second part of the paper, we complement our analytical findings with numerical simulations using a computable general equilibrium (CGE) model calibrated to empirical data for the EU. We find that all qualitative results from the theoretical analysis still hold in the much more complex general equilibrium setting. The CGE framework does not only accommodate the quantification of policy-induced changes in the economic and environmental indicators underlying the theoretical analysis. It also provides insights into the scope for burden shifting through overlapping regulation. In particular, we find that under the unilateral tax also the other countries share the economic adjustment costs of emission reductions, but not so if there is an ETS II and emission allowances are cancelled unilaterally. Moreover, the scenario with a second ETS allows us to compare the symmetric policies of unilaterally cancelling allowances in either the ETS for the power sector or the ETS II for the buildings and transport sectors. It turns out that the latter leads to substantially lower welfare losses — EU-wide as well as for the individual regions that we consider. In conclusion, our analysis shows that accounting for sector coupling leads to strong arguments for targeting unilateral policies to the OEC sectors (transport/heating), rather than to the ETS sector (electricity).

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. Similar to our paper, Eichner and Pethig (2009) also consider an emissions tax in the OEC sectors that overlap with an ETS. However, their main focus lies on how this affects a country's incentive to set its cap for the ETS, which is exogenous in our analysis. As mentioned above, the literature that considers overlapping policy interventions within the ETS sector is substantially larger. Unless allowances are cancelled,

[2] The realisation and the specific rules still have to be decided formally. Currently, it is planned that this ETS II starts in 2027 and that additional allowances are released if their price exceeds € 45 over a certain period of time. This is substantially below the allowance price of the existing EU ETS, showing that the two systems should indeed be treated as separate ones. See, e.g., https://www.consilium.europa.eu/en/press/press-releases/2022/12/18/fit-for-55-council-and-parliament-reach-provisional-deal-on-eu-emissions-trading-system-and-the-social-climate-fund/.

such policies like support schemes for renewables (Böhringer and Rosendahl, 2010) or a unilateral coal phase-out (Anke, Hobbie, Schreiber, and Möst, 2020; Böhringer and Rosendahl, 2022; Eichner and Pethig, 2021) are prone to the waterbed effect and tend to lower the ETS price, from which CO_2-intensive power production, especially coal, benefits the most.

Yet, the literature has stressed the need take into account feedback effects resulting from interlinkages with other sectors not covered by the ETS. An early contribution is Baylis, Fullerton, and Karney (2014) who examines this analytically and numerically using a two-sector model, where the CO_2 tax in one sector is increased (see also Baylis, Fullerton, and Karney, 2013). They even find that negative leakage may occur when the taxed sector draws resources away from the other sector or country, which reduces output and emissions in these segments. However, Winchester and Rausch (2013) investigate this leakage mechanisms in a CGE model and show that to generate net negative leakage fossil fuel supply elasticities must be close to infinity, whereas the bulk of empirical estimates indicate values which are less than unity.

Jarke and Perino (2017) extend the model of Baylis et al. (2014) by considering two technologies (clean and dirty) instead of one in the emissions-capped sector. They then analyse the effects of overlapping regulatory policies (ETS for electricity sector, CO_2 tax in non-electricity sector, feed-in tariffs for green electricity) that drive substitution between clean and dirty technologies. Our analytical model goes one step further by including two technologies in the OEC sector as well, which allows us to represent sector coupling explicitly. Two further contributions of these authors use similar models but consider different policies: climate campaigns in Perino (2015) as well as renewable energy promotion in Jarke-Neuert and Perino (2020). Perino, Ritz, and van Benthem (2019) develop a general framework for analysing different unilateral policies that overlap with wider CO_2 pricing systems such as an ETS. They focus on how to separate and evaluate internal carbon leakage in the product market and waterbed effects. 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 that are central for our paper. Moreover, although some of the cited articles complement a theoretical analysis with numerical simulations, this is not done within a fully fledged CGE model.

The remainder of the paper starts with the theoretical analysis in Section 2. After describing the analytical model in Subsection 2.1, we analyse unilateral CO_2 taxes and subsidies in the OEC sectors (Subsection 2.2), and the cancellation of allowances (Subsection 2.3). The numerical analysis in Section 3 starts with a non-technical summary of the CGE model and the empirical data used for model calibration (Subsection 3.1), and then explains the specific scenarios for the simulations (Subsection 3.2). Thereafter, we contrast the results of the analytical model with those from the numerical simulations (Subsection 3.3) and examine welfare effects (Subsection 3.4). Section 4 concludes. Appendices A and B contain the proofs and a more detailed algebraic description of the CGE model.

2 Theoretical analysis

2.1 Analytical model

Consider a set of $N = \{1, ..., n\}, n \geq 2$ jurisdictions that are indexed i. In the remainder we refer to them as "countries", but the analysis also applies to national emissions trading systems (ETS) where the individual regions have some discretion in choosing complementary environmental policies. Examples include the Regional Greenhouse Gas Initiative (RGGI) in the US and China's ETS, as well as the linkage between the ETS in California and Quebec that covers regions in different countries.

We split the economy of each country into an ETS sector that comprises the power sector and an OEC sector that covers all other energy consuming activities with the potential for "electrification" (sector coupling). Thus, the only output of the ETS sector is electricity (denoted y), whereas the most relevant outputs of the OEC sector are transport and heating/cooling of buildings (denoted x). For parsimony, we sometimes refer to the ETS and OEC sectors as the electricity and transport sector, 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 country i, and so on. The dirty technologies use fossil fuels as an input; e.g., coal plants for electricity generation, internal-combustion-engines for vehicles and oil- or gas-boilers for heating. 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 OEC sector.[3]

Total transport and electricity supply are $x_i^S = x_{ci} + x_{di}$ and $y_i^S = y_{ci} + y_{di}$. Note that here and in the remainder we skip the addendum "for $i \in N$" as well as superscripts S for supply and D for demand 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 $e_{xi} = \alpha_x x_{di}$ and $e_{yi} = \alpha_y y_{di}$, where $\alpha_x, \alpha_y > 0$ 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 differences of production technologies across countries, as well as the possibilities of efficiency improvements (e.g., fuel economy-boosting technologies) and of switching to less CO_2 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 technologies. Given this simplification, we can denote the cost functions that result from firms' cost minimization problems in the ETS and OEC sectors (superscripts y and x) by $C_{ci}^y(y_{ci}), C_{di}^y(y_{di})$, and $C_{di}^x(x_{di})$.[4]

Electric vehicles and heat pumps — the most relevant "clean" technologies in the OEC sector — are special in that they use 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. Specifically, we assume that electricity input in the OEC sector is proportional to output. This appears reasonable if one thinks of transport 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 x_{ci} units of clean transport 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 transport (or heating) services.

We adopt the standard assumption that all cost functions are twice continuously differentiable with $C'_{ki}(\cdot) > 0$ and $C''_{ki}(\cdot) > 0$, $k = c, d$. 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. Transport and heating depend on location, and we assume that it is only traded on national markets at country-specific prices p_{xi}. For electricity, there typically exists cross-country trade, which is however limited by transmission capacities. In our analytical model, we assume 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 trade patterns of electricity. In the CGE model we relax this assumption and accommodate cross-country electricity trade.

In each country, a representative household 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. Here, $u_i(x_i)$ captures the utility from transport/heating, whereas $u_i(y_i)$ can be interpreted loosely as utility from the consumption of goods that require considerable amounts of electricity — like cooking and washing laundry. 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 strictly concave.

Throughout the article, we assume that the electricity sector is regulated by an ETS with auctioned allowances, an exogenous emissions cap $\bar{e}_y$, and an endogenous allowance price ν. For the OEC sector, we first consider the case that it has no ETS. A unilateral policy in this sector then takes the form of

[3] Obviously, this simple labelling neglects that (i) the production of wind mills, solar panels, or electric vehicles may lead to CO_2 emissions, and (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 our numerical CGE simulations.

[4] 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).

a unilateral increase of either the tax, τ_A, per unit of emissions from the dirty technology, or of the subsidy, σ_A, per unit of output from the clean technology, where A denotes the country (region) that implements the unilateral policy (i.e., $d\tau_j, d\sigma_j = 0$ for all other countries $j \in N \backslash A$).

In line with recent decisions in the EU, we also consider the alternative case that the OEC sector is also regulated by an "ETS II" — though a separate one — with an exogenous emissions cap $\bar{e}_x$ and an endogenous allowance price φ. In this case, the policy intervention is a unilateral cancellation of ζ allowance units.

The (concave) profit functions for the respective firms are given as the difference between revenues, production costs and payments for emissions. Their specification below covers all three potential policy instruments, but in the subsequent analysis only one of them will be active in turn (π^y_{di} are profits of the representative firm in the dirty electricity sector of country i, and so on):

$$\pi^y_{di}(y_{di}) = p_{yi}y_{di} - C_{di}(y_{di}) - \nu e_{yi}, \tag{1}$$
$$\pi^y_{ci}(y_{ci}) = p_{yi}y_{ci} - C_{ci}(y_{ci}), \tag{2}$$
$$\pi^x_{di}(x_{di}) = p_{xi}x_{di} - C_{di}(x_{di}) - (\tau_i + \varphi)\, e_{xi}, \tag{3}$$
$$\pi^x_{ci}(x_{ci}) = p_{xi}x_{ci} - C_{ci}(x_{ci}) - (p_{yi}\beta - \sigma_i)\, x_{ci}. \tag{4}$$

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

$$p_{yi} = C'_{di}(y_{di}) + \nu\alpha_y, \tag{5}$$
$$p_{yi} = C'_{ci}(y_{ci}), \tag{6}$$
$$p_{xi} = C'_{di}(x_{di}) + (\tau_i + \varphi)\,\alpha_x, \tag{7}$$
$$p_{xi} = C'_{ci}(x_{ci}) + p_{yi}\beta - \sigma_i. \tag{8}$$

The expressions have the familiar interpretation that output prices are equal to marginal production costs after accounting for the policy instruments. Moreover, in each of the two sectors the price and, thus, marginal costs are the same for the respective dirty and the clean technologies.

Turning to consumers, the budget constraint obviously binds. Solving it for z and substitution into the (concave) utility function yields the first-order conditions that marginal utility equals prices for all $i \in N$:

$$u'_i(y_i) = p_{yi}, \tag{9}$$
$$u'_i(x_i) = p_{xi}. \tag{10}$$

Prices follow from the respective market clearance conditions that demand equals supply. These are for the allowance market(s) (Eqs. (12) only applies if there is an ETS II in which ζ allowances are cancelled)

$$\sum_{i\in N} \alpha_y y_{di}(\nu) = \bar{e}_y, \tag{11}$$
$$\sum_{i\in N} \alpha_x x_{di}(\varphi) = \bar{e}_x - \zeta, \tag{12}$$

where we have used $e_{yi} = \alpha_y y_{di}$ and $e_{xi} = \alpha_x y_{xi}$. Similarly, market clearance requires for the OEC sector

$$x^D_i(p_{xi}) = x^S_{di}(p_{xi}) + x^S_{ci}(p_{xi}),\ i \in N, \tag{13}$$

and for the ETS sector

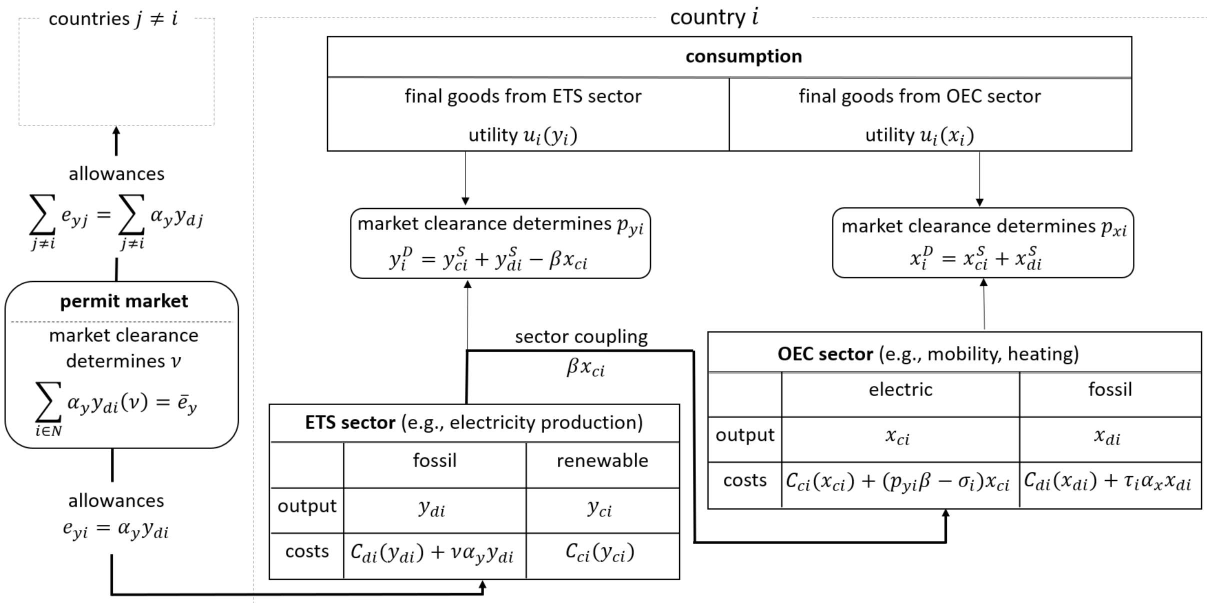
$$y^D_i(p_{yi}) = y^S_{di}(p_{yi}) + y^S_{ci}(p_{yi}) - \beta x_{ci},\ i \in N, \tag{14}$$

where $\beta x_{ci} = y_{xi}$ is electricity input into clean transport. In the case of an ETS II, this yields a system of $8n + 2$ equations that determines the $4n$ output values, $2n$ consumption values, and $2n + 2$ prices. Without an ETS II there is one equation and one price less.

2.2 Unilateral climate policies if the OEC sector has no ETS

Figure 1 graphically illustrates the analytical model for the case of no ETS II. In each country i, households consume the output of the ETS and OEC sectors that can be produced alternatively by a clean or dirty (= fossil) technology. The clean (electricity-based) technology in the OEC sector requires the output of the ETS sector as an input. This "linkage between sectors" is represented by the bold vector labelled "sector coupling". Moreover, the ETS sector requires emissions allowances as an input, which are traded on an international permit market. This leads to a "linkage between countries" as represented by the left bold arrow labelled "allowances". These two interlinkages drive the indirect effects that a unilateral policy in the OEC sector — an emissions tax τ_i or a renewables subsidy σ_i — has on the other sectors and countries.

Fig. 1: Structure of analytical model



Proposition 1 identifies how these effects change the output and consumption values as well as prices that arise in response to a unilateral policy. More specifically, we consider the effects of a marginal increase of either the tax or subsidy in the OEC sector of the country (or region) that undertakes unilateral action, indexed A. As the resulting comparative static effects do not depend on the tax/subsidy levels before their marginal increase, the results also apply to larger, non-marginal policy interventions — such as those that we later consider in the numerical simulations.

Proposition 1. *(Effects of unilateral tax or subsidy) Let there be a country (or group of countries), indexed A, that in the OEC sector unilaterally raises either the tax on emissions from the dirty technology or the subsidy for the clean technology; i.e., $d\tau_A > d\tau_j = 0$ or $d\sigma_A > d\sigma_j = 0$, where $j \in N\backslash A$ indexes all other countries that do not raise their tax or subsidy.*

a) *The allowance price in the ETS-sector rises ($d\nu > 0$). Output prices rise for all countries in both sectors with one exception: it falls in the OEC sector of country A if it implements a subsidy (i.e., if $d\tau_A > 0$, then $dp_{yi}, dp_{xi} > 0 \;\forall\, i \in N$; if $d\sigma_A > 0$, then $dp_{yi} > 0 \;\forall\, i \in N$, $dp_{xA} < 0$, and $dp_{xj} > 0$).*

b) *Effects in OEC sector (transport/heating): In country A, output of the dirty technology falls and output of the clean technology rises ($dx_{dA} < 0, dx_{cA} > 0$). In all other countries, this patter is reversed ($dx_{dj} > 0, dx_{cj} < 0$). Overall output and, thus, consumption, falls in country A if it* *implements a tax ($dx_A < 0$ if $d\tau_A > 0, d\sigma_A = 0$), but rises in the case of a subsidy ($dx_A > 0$ if $d\tau_A = 0, d\sigma_A > 0$). In the other countries, overall output and consumption always fall ($dx_j < 0$).*

c) *Effects in ETS sector (electricity): Output of the dirty technology rises in country A, but falls in the other countries ($dy_{dA} > 0, dy_{dj} < 0$). In all countries, output of the clean technology rises ($dy_{ci} > 0, i \in N$), whereas consumption falls ($dy_i < 0, i \in N$).*

Intuitively, a tax on dirty transport and a subsidy on clean transport by country A both induce a shift from dirty to clean transport, hence $dx_{dA} < 0$ and $dx_{cA} > 0$. As clean transport requires more electricity, production from both dirty and clean sources goes up so that $dy_{dA}, dy_{cA} > 0$. In order to induce firms in country A to produce more electricity, the associated price must be higher ($dp_{yA} > 0$). This raises production cost of clean transport because it uses electricity as an input. Together with the tax on dirty transport, the price of transport rises ($dp_{xA} > 0$). Moreover, the higher supply of dirty electricity drives up the allowance price ($d\nu > 0$), which makes production of dirty electricity in the other countries more expensive. Hence their supply falls ($dy_{dj} < 0$) which is (partly) compensated by more clean electricity ($dy_{cj} > 0$). Finally, as the higher allowance price raises production cost of electricity, its price goes up ($dp_{yj} > 0$), which makes electricity powered clean transport in the other countries more costly. Hence it falls ($dx_{cj} < 0$) and the transport price rises ($dp_{xj} > 0$), which raises the profitability of dirty transport ($dx_{dj} > 0$). The main difference between the two instruments is that the tax disincentivizes dirty transport, whereas the subsidy fosters clean transport. Therefore, overall transport in country A falls with a tax but rises with a subsidy.

We now turn to the analysis of emissions, whose reduction is the underlying objective of the unilateral policy in the OEC sector. By assumption, there is a deterministic relation between the output of the dirty technologies and associated emissions. Therefore, the latter follow straightforwardly from $de_{yi} = \alpha_y dy_{di}$ and $de_{xi} = \alpha_x dx_{di}$, using Proposition 1. Accordingly, the unilateral policy intervention has opposing effects in country A and in the other countries. For the latter, output and emissions of dirty transport/heating rises, whereas their output of dirty — i.e., fossil-fuel-based — electricity production and associated emissions fall. This represents the reverse waterbed effect: as the switch to sector-coupling technologies in the unilateral action country requires more electricity (and emissions), the other countries' share of capped emissions in the ETS decreases.

Due to the countervailing effects across sectors, the sign of the change in overall emissions of the individual countries, $de_i = \alpha_x dx_{di} + \alpha_y dy_{di}$, depends on the specific parameter constellation. The aggregate effect on emissions in the ETS sector is zero by construction due to the exogenous cap in this sector. Thus, the total emissions effect is determined in the uncapped OEC sector. A priori, this is ambiguous because country A's unilateral policy reduces domestic emissions from transport, but raises those in the other countries due to a higher electricity price. The following proposition shows that in the case of a tax its direct effect on discouraging emissions in country A dominates so that the overall level of dirty transport and, thus, overall emissions fall. By contrast, the subsidy addresses emissions only indirectly by improving the competitiveness of clean substitutes (such as electricity-based transport or heating). Therefore, emissions effects in country A are weaker and the overall effect is ambiguous. Nevertheless, the overall output of the clean technology in the OEC sector rises under the tax as well as under the subsidy ($\sum_{i \in N} dx_{ci} > 0$).

Proposition 2. *(Comparison of emissions and aggregate effects) Let there be a country (or group of countries), indexed A, that in the OEC sector unilaterally raises either the tax on emissions from the dirty technology or the subsidy for the clean technology; i.e., $d\tau_A > d\tau_j = 0$ or $d\sigma_A > d\sigma_j = 0$, $j \in N \backslash A$.*

(a) *Sector specific emissions: In country A, emissions fall in the OEC sector (transport/heating) but rise in the ETS-sector (electricity) ($de_{xA} < 0, de_{yA} > 0$). In the other countries this pattern is reversed ($de_{xj} > 0, de_{yj} < 0$).*

(b) *Overall emissions: Overall output of the clean technology in the OEC sector rises ($\sum_{i \in N} dx_{ci} > 0$). If country A implements a tax, overall emissions and the overall output of the dirty technology fall ($de < 0, \sum_{i \in N} dx_{di} < 0$), whereas this need not be the case if it implements a subsidy.*

Obviously, these results come with the caveat that skipping some of the model's simplifying assumptions such as additive separability of utility and incorporating general equilibrium effects — e.g., mobility of capital and labour across sectors — would change this. Nevertheless, the fact that the later numerical results from the CGE model are consistent with the above Propositions suggests that the simple analytical model does actually capture the most relevant effects for the issue at stake.

2.3 Unilateral climate policies if also the OEC sector has an ETS

In line with recent policy decisions in the EU, we now consider the case that also the OEC sector is regulated by an emissions trading system, called ETS II. Therefore, the policies that we have analysed so far — taxes for the dirty and subsidies for clean technology in the OEC sector — have no impact on total emissions if the caps in the two ETS are assumed to be fixed. However, the ETS II opens up the new policy option to cancel emission allowances in the OEC sector.

Intuitively, this drives up the allowance price in that sector ($d\varphi > 0$), making its dirty technology more costly. Hence its output as well as overall output of the OEC sector fall in all countries ($dx_{di}, dx_i < 0, i \in N$). Accordingly, these effects are more symmetric across countries than those of a unilateral tax or subsidy in Proposition 1 because they are induced by a change in the *common* allowance price. The clean technology in the OEC sector is not directly affected by the higher allowance price; hence its relative competitiveness improves and its total output rises ($\sum_{i\in N} dx_{ci} > 0$).

Due to sector coupling, this leads to a higher electricity demand. Therefore, clean electricity production rises ($dy_{ci} > 0$), and the cap on emissions of dirty electricity leads to a higher allowance price in the ETS ($d\nu > 0$). This redirects some dirty electricity production to those countries that have more favourable cost functions so that also their overall electricity output increases. In these countries output of clean transport increases, whereas this need not be the case for the other group of countries in which the output from dirty electricity falls. The following proposition summarizes the main results.

Proposition 3. *(Unilateral cancellation of allowances in ETS II) Suppose that the sectors in the economy are regulated by two separate emissions trading systems, and a country (or group of countries) cancels emission allowances in the ETS II of the OEC sector.*

a) *The allowance price rises in both ETS ($d\nu, d\varphi > 0$).*

b) *Effects in OEC sector (transport/heating): In each country, output of the dirty technology as well as overall output fall ($dx_{di}, dx_i < 0, i \in N$). For the clean technology, aggregate output of all countries rises ($\sum_{i\in N} dx_{ci} > 0$).*

c) *Effects in ETS sector (electricity): In each country, output of the clean technology rises ($dy_{ci} > 0, i \in N$), whereas consumption falls ($dy_i < 0, i \in N$).*

A symmetric policy is the cancellation of allowances in the ETS for the electricity sector, which has been analysed, e.g., as a complementary measure to a unilateral coal phase-out. Intuitively, the effects in the respective sectors where allowances are cancelled are symmetric and favour the clean as compared to the dirty technology. However, the cross-sectoral effects that arise from sector coupling are quite different. In particular, cancelling ETS II allowances also leads to a higher output of the clean technology of the other sector ($\sum_{i\in N} dy_{ci} > 0$). By contrast, if ETS allowances are cancelled, this raises the electricity price and overall output of electricity-based, clean transport falls ($\sum_{i\in N} dx_{ci} < 0$). The latter policy is therefore at odds with the generally accepted goal of electrifying all sectors of the economy. The proposition summarizes this and some further results.

Proposition 4. *(Unilateral cancellation of allowances in ETS) Suppose that the sectors in the economy are regulated by two separate emissions trading systems, and a country (or group of countries) cancels emission allowances in the ETS of the electricity sector.*

a) *The allowance price rises in both ETS ($d\nu, d\varphi > 0$).*

b) Effects in OEC sector (transport/heating): In each country, overall output falls ($dx_i < 0, i \in N$). For the clean technology, aggregate output of all countries falls ($\sum_{i \in N} dx_{ci} < 0$).

c) Effects in ETS sector (electricity): In each countries, output of the clean technology rises ($dy_{ci} > 0, i \in N$), whereas output of the dirty technology and consumption fall ($dy_{di}, dy_i < 0, i \in N$). Total electricity generation falls ($\sum_{i \in N}(dy_{di} + dy_{ci}) < 0$).

3 Numerical analysis

In the preceding theoretical analysis, we neglected various real-world features that might be important for drawing viable policy conclusions. For example, countries are not only linked via the ETS but engage in bilateral trade on commodity markets, which creates additional spillover effects. Moreover, economic adjustments triggered by policy interventions are driven through a variety of substitution, output, and income effects that are substantially more complex than represented in the analytical model with its simple specification of preferences and production technologies. We therefore complement our theoretical analysis with computable general equilibrium (CGE) simulations based on empirical data. The quantitative impact assessment not only accommodates a robustness check on the qualitative results of the theoretical analysis, but also delivers policy-relevant insights into the magnitude of economic adjustment.

We first address specific model features in the context of sector coupling, describe the data sources for model parameterization, and set out the anchoring of our scenarios in current EU climate policies. Then, we discuss the simulation results, relate them to the findings of the theoretical analysis, and provide a cost-effectiveness ranking of alternative policy options for unilateral emission reductions.

3.1 Model and data

Our numerical model adopts the standard top-down CGE structure for representing production, consumption, and trade (see, e.g., Böhringer, Carbone, and Rutherford, 2018). For parsimony, we focus here on the non-standard bottom-up representation of alternative power generation technologies and sector coupling possibilities, which are central to our analysis. A summary of all basic model features together with an algebraic model description is provided in Appendix B.

The technological options in the power sector are of paramount importance for the decarbonization of economic activities. In particular, electricity generation by renewable energy sources does not only provide an option to substitute fossil-fuel-based power production, but it is also key to the greening of energy demand in other sectors via sector coupling. We therefore distinguish different power generation technologies that produce electricity by combining inputs of labour, 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 decreasing 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, we introduce the options to substitute energy demands of fossil fuels (coal, oil, and gas) in production and consumption directly by electricity (see Figure 3 in Appendix B). Examples of such direct electrification are the replacement of oil-fired heating systems with electric heat pumps (power-to-heat) and the use of electric motors in vehicles (power-to-transport) instead of gasoline or diesel engines. 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 are calibrated in accordance with exogenous supply elasticities that capture the ease of sector coupling for the specific fossil energy carrier in intermediate and final demands.

Regarding international trade in electricity, we adopt the standard Armington (1969) assumption of differentiated regional goods, which accommodates the empirical observation that a country imports and exports the same good (so-called cross-hauling). Trade elasticities indicate the degree of substitutability and capture implicitly physical restrictions by transmission capacities or hedging strategies through supply diversification.

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 behaviour 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, Saveyn, and Soria Ramirez, 2018; Rey Los Santos, Wojtowicz, Tamba, Vandyck, Weitzel, Saveyn, and Temursho, 2018). The JRC data include detailed macroeconomic accounts on production, consumption, and bilateral trade together with information on physical energy flows and CO_2 emissions for 40 regions and 31 sectors covering all EU countries and their main trading partners in the world economy. The electricity sector in the JRC dataset is decomposed by region into 11 discrete generation technologies and a composite 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 against which we measure the implications of policy interventions such as unilateral emissions pricing in the OEC sectors. The initial allocation of emission allowances under the ETS follows EU regulations.[5]

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 in 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). For hydrogen and nuclear power we assume that generation can not exceed the JRC benchmark level in 2030 reflecting natural resource limits and policy constraints across EU countries.

Regarding supply elasticities for power-to-X technologies, we are not aware of representative empirical studies so far. This reflects that such technologies only just start being operated at a larger scale because they are often not yet profitable without subsidies. In our numerical implementation, we therefore assume the initial 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 CO_2 pricing) increase and sector coupling becomes attractive. Sensitivity analysis on a broader range of cost gaps and elasticity assumptions confirms the robustness of our findings.

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 to distinguish energy goods by CO_2 intensity and the degree of substitutability. In addition, we include a composite of emissions-intensive and trade-exposed (EITE) industries covered by the EU ETS (i.e., chemical products, non-metallic minerals, iron and steel, nonferrous metals, and air transport). The rest of other industries and services which — beyond final consumption — constitute the OEC sectors of the economy are represented by an aggregate com-

[5] For the 57 per cent of allowances that are auctioned, Member States' shares during the period 2021-2030 are taken from the COMMISSION DECISION (EU) 2020/2166). For the remaining 43 per cent of allowances, we assume that they are allocated in proportion to the verified emissions under the EU ETS for 2005 (or the average of the period from 2005 to 2007, whichever one is the highest), noting that this is also the main criterion for the allocation of auctioned allowances. Data are taken from the EU Emissions Trading System (ETS) data viewer (https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1). The actual allocation procedure for these freely allocated allowances is substantially more complex and based on National Allocation Plans that countries submit to the Commission. These plans are submitted on a year to year basis and, therefore, are not available for 2030.

modity. 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 CO_2 emissions abatement both in the ETS and OEC sectors of the economy.

The regional coverage in the dataset reflects our focus on unilateral emissions reduction policies by a group of environmentally ambitious countries in Europe, to which we later refer to as "climate coalition", or simply COA (see Section 3.2). For the OEC sectors, the EU effort sharing regulation (ESR) specifies country-specific emissions reduction targets for 2030 compared to their 2005 levels (Regulation (EU) 2018/842, Annex I). We sort countries according to the stringency of emissions reduction targets under the ESR. The most ambitious group compromises countries with reduction targets above 35%. Of these we keep Germany, France, and the United Kingdom[6] as large countries, whereas the other countries from this group are attributed to a composite region, labelled R35. Next, there is a regional aggregate with moderate (25-35%) ambition targets, labelled R25, followed by two composite regions with targets below 25% — labelled EEC for the Eastern European countries and REU for the residual consisting of mainly smaller EU countries. Of the EEC group, we keep Poland as a politically important country whose electricity generation is predominantly based on coal. Finally, for the sake of compactness, we limit the explicit representation of the remainder of the global economy to a single 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

Sectors	Regions
ETS sectors	**Members of climate coalition (COA)**
Refineries	*Individual countries*
Refined petroleum products	Germany, United Kingdom, France
Emission-intensive and trade-exposed sectors	*R35 (high targets >35%)*
Composite of chemical products, non-metallic minerals, iron and steel, non-ferrous metals, paper products and publishing, air transport	Composite of Austria, Denmark, Finland, Netherlands, Luxembourg, Sweden *R25 (moderate targets >25% and <35%)* Composite of Belgium, Italy, Ireland, Spain
Electricity	**Non-members (NCOA)**
Discrete power generation by fossil fuels (coal, oil, gas), nuclear, and renewables (wind, hydro, biomass, solar)	Poland *EEC: Eastern European Countries*
OEC sectors	Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Romania, Slovakia, Slovenia
Primary fossil fuel extractive sectors	
Coal, crude oil, natural gas	*REU: Rest of Europe*
Rest of industry and services	Greece, Malta, Portugal, Cyprus
Composite of all other remaining industrial and service sectors in JRC dataset	**Rest of World**
Final consumption	All other countries and regions in JRC dataset
Household and government demands	

3.2 Climate policy scenarios

In our simulation analysis, we focus on 2030 as a milestone year for EU climate policies. The JRC dataset already incorporates the EU's initial 2030 target of a 40% greenhouse gas emissions reduction as compared to 1990, reflecting the pledge that the EU made 2015 under the Paris Agreement. For

[6] The UK left the EU ETS in 2020 following Brexit and formed a UK ETS. Nevertheless, in our analysis we treat it as part of the EU ETS because it appears likely that the two systems will be linked until 2030, which is the milestone year for our climate policy assessment.

the 2030 benchmark situation, to which our model is calibrated, the JRC dataset reports an ETS allowance price of 39 $\$/tCO_2$, while emissions prices for OEC sectors in the EU are initially zero.

More recently, 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" (Fit-55) of law reform proposals (COM(2021) 551 final). This package aims to raise the reduction target for 2030 to 55%, which is equivalent to a reduction of EU emissions under the original 2030 target by an additional 25%. We argue that the existence of a common cap in the ETS sectors facilitates an EU-wide agreement on a further reduction of ETS emission allowances by this 25%, and we take this as our reference scenario, called *ref.* Its ETS allowance price is 96.9 $\$/tCO_2$.

The *ref* scenario leaves a gap to Fit-55 because its emission reductions are restricted to the ETS sectors, which in the benchmark situation account for only 49% of overall EU-wide emissions. We assume that this gap is closed by *unilateral* action of environmentally more concerned EU member states, denoted as the climate coalition "COA". To determine this group, we use the fact that for the OEC sectors the effort sharing regulation (ESR) specifies different emissions reduction targets for the individual member states (see above). We argue that ESR reduction targets below 25% reflect lower ambitions and assume that this group (called "NCOA") is unwilling to increase its emission reductions beyond those in the *ref* scenario. By contrast, for the countries with ESR targets above 25% — the climate coalition as of Table 1 — we assume that they are willing to *unilaterally* fill the gap such that *overall* EU emissions meet the Fit-55 target.

We examine three different scenarios to achieve this, which closely follow our theoretical analysis. They are specified such that for all scenarios overall emission reductions are the same, and the same level of reductions can be attributed to the unilateral action. In the first scenario, called *tax-OEC*, coalition countries set a *unilateral* CO_2 price on emissions in their OEC sectors, at a level sufficient to reduce *EU-wide* emissions in the OEC sectors by the required 25%.[7] The second scenario, called *kill-OEC,* takes up recent EU climate policy plans to establish a second emissions trading regime (the so-called ETS II) for emissions in the OEC sectors of all EU member states. In this scenario, an ETS II is already in place before the implementation of the unilateral emissions reduction policy, and we assume that the initial endowment with ETS II allowances corresponds to countries' emissions in scenario *ref.* The unilateral policy is then for coalition countries to cancel (or "kill") enough ETS II allowances to meat the overall Fit-55 target. In the third scenario, called *kill-ETS,* coalition countries cancel an equivalent amount of allowances in the existing EU ETS.[8] In addition, cooperative reductions of all EU countries in the OEC sectors now fill the gap to achieve the Fit-55 target.[9]

Table 2 summarizes the EU-wide and unilateral policies in the ETS and OEC sectors for the different scenarios. Note that in the acronyms for the unilateral action scenarios the first part always refers to the instrument and the second part to the sector where it is implemented.

3.3 Numerical results: Effects on emissions and electricity markets

For our three scenarios, Table 3 compares the signs of the comparative statics from our analytical model in Propositions 1 to 4, with the corresponding quantitative effects in the numerical CGE model. The latter are given both as percentage and absolute changes compared to the *ref* scenario; hence they capture the effects of the unilateral action by the climate coalition COA.

While the numerical model is substantially more complex and features several additional linkages

[7] Note that such a uniform price for OEC emissions of all coalition countries (while OEC emissions for non-coalition countries remain unpriced) can be obtained equivalently by an emissions trading system that is restricted to the OEC sectors of coalition countries. In the algebraic model code we adopt this approach as it simplifies the implementation of our quantitative emissions reduction target. Moreover, in the *tax-OEC* scenario, emissions in the OEC sectors of non-coalition countries are unconstrained and change due to general equilibrium interaction effects. Hence, the allocation of allowances for the coalition countries is scaled endogenously such that EU-wide OEC emissions are reduced by 25%. The allocation of emission allowances to the individual coalition countries is based on their emissions in the *ref* scenario.

[8] In both scenarios, coalition countries contribute to the cancellation of allowances in proportion to their emissions in the *ref* scenario.

[9] Cooperative action is implemented as a uniform downscaling of ETS II allowances across all EU countries.

Tab. 2: Policy scenarios

		ref	*tax-OEC*	*kill-OEC*	*kill-ETS*
ETS sectors	EU-wide policy	uniform 25% reduction of initial (benchmark) EU emission allowances	uniform 25% reduction of initial (benchmark) EU emission allowances	uniform 25% reduction of initial (benchmark) EU emission allowances	none
	Unilateral policy	none	none	none	unilateral killing of same amount of allowances as in *kill-OEC**
OEC sectors	EU-wide policy	none	none	none	uniform reduction of allowances to achieve Fit-55
	Unilateral policy	none	unilateral emissions pricing to achieve Fit-55 target	unilateral killing of allowances to achieve Fit-55 target	none

* Emission allowances of non-coalition countries remain at the level of their *ref* emissions.

such as trade in electricity or intermediate input-output relationships between ETS and OEC sectors, all of the listed changes are consistent with the results from the analytical model. Moreover, the simulation results fill the gaps where the analytical results have been ambiguous. They also reveal that even if the impacts of different scenarios have the same sign in the analytical model, the quantitative differences can be significant.

For example, the first row in Table 3 shows that the emissions price in the OEC sectors rises for all three scenarios. Moreover, *tax-OEC* and *kill-OEC* both implement the same overall emission reductions in the OEC sectors. Nevertheless, the necessary unilateral tax of 125 $\$/tCO_2$ substantially exceeds the corresponding CO_2 price of 70.1 $\$/tCO_2$ that results from the unilateral cancellation of allowances in the ETS II. This reflects that *kill-OEC* provides the same CO_2 price signal to all countries so that substantial efficiency gains from where-flexibility of emissions abatement in OEC sectors across all EU countries materialize. By contrast, the unilateral tax in scenario *tax-OEC* must be higher because it incentivices only emission reductions in the OEC sectors of COA countries (by 32.9%), whereas OEC emissions in NCOA even increase (by 0.8%).

Higher CO_2 prices in the OEC sectors make fossil-fuel-based technologies less attractive and foster electrification of, e.g., transport and heating. Under *tax-OEC*, this sector coupling effect and the resulting higher electricity demand occurs only in COA countries, where the unilateral tax is imposed. Accordingly, electricity generation in COA increases by 201 TWh, whereas in NCOA it even falls by 10.4 TWh. Under *kill-OEC*, the theoretical analysis showed that sector-coupling technologies and the associated electricity generation rise in the aggregate, but region-specific effects were inconclusive. The numerical results show that electricity generation increases in both regions, but most of the additional generation takes place in COA (both in percentage and absolute values), indicating that sector coupling is again stronger in this region. This reflects that the higher electricity demand is confronted with an emissions cap in the ETS sectors so that the ETS allowance price rises (by 13.3 $\$/tCO_2$ in the *kill-OEC* scenario), making electricity more costly. NCOA is affected substantially more by this and, thus, faces a higher increase of electricity prices than COA because it has a larger share of CO_2-intensive coal in the reference scenario. Accordingly, electricity generation from fossils falls by 7.9 TWh for NCOA, but rises by 58.6 TWh for COA.

This also explains that emissions in the ETS sectors rise for COA (by 3.1% in *tax-OEC* and 1.8% in *kill-OEC*), but fall for NCOA (by -6.9% in *tax-OEC* and -3.9% in *kill-OEC*). Especially

Tab. 3: Unilateral emissions pricing in OEC sectors — results from analytical and numerical model

change of ...		analytical model: sign of change *tax-OEC*	*kill-OEC*	*kill-ETS*	numerical model: % change to *ref* *tax-OEC*	*kill-OEC*	*kill-ETS*	absolute change to *ref* *tax-OEC*	*kill-OEC*	*kill-ETS*
emissions price	OEC sector	$d\tau_A > 0$	$d\varphi > 0$	$d\varphi > 0$				125 $/t$CO_2$*	70.1 $/t$CO_2$	6.6 $/t$CO_2$
	ETS sector	$d\nu > 0$	$d\nu > 0$	$d\nu > 0$	12.5	13.7	87.8	12.1 $/t$CO_2$	13.3 $/t$CO_2$	85.1 $/t$CO_2$
emissions in	COA	$de_{xA} < 0$	$de_{xA} < 0$	$\sum de_{xi} = 0$	−32.9	−25.9	−0.3	−332 MtCO_2	−262 MtCO_2	−3 MtCO_2
OEC sector	NCOA	$de_{xj} > 0$	$de_{xj} < 0$		0.8	−25	1.1	2.1 MtCO_2	−67.9 MtCO_2	3 MtCO_2
emissions in	COA	$de_{yA} > 0$	$\sum de_{yi} = 0$	$de_{yA} < 0$	3.1	1.8	−26.6	19.7 MtCO_2	11.2 MtCO_2	−169 MtCO_2
ETS sector	NCOA	$de_{yj} < 0$		$de_{yj} < 0$	−6.9	−3.9	−56.3	−19.7 MtCO_2	−11.2 MtCO_2	−160 MtCO_2
total emissions	COA	?	?	?	−18.9	−15.2	−10.5	−312 MtCO_2	−251 MtCO_2	−173 MtCO_2
	NCOA	?	?	?	−3.2	−14.2	−28.2	−17.6 MtCO_2	−79 MtCO_2	−157 MtCO_2
	all	$de < 0$	$de < 0$	$de < 0$	−15	−15	−15	−330 MtCO_2	−330 MtCO_2	−330 MtCO_2
electricity price	Germany	$dp_{yA} > 0$	$dp_{yA} > 0$	$dp_{yA} > 0$	1.5	1.4	6.9	0.5 Ct/KWh	0.4 Ct/KWh	2.1 Ct/KWh
(consumers)	EEC	$dp_{yj} > 0$	$dp_{yj} > 0$	$dp_{yj} > 0$	1.5	2.8	13.6	0.3 Ct/KWh	0.5 Ct/KWh	2.5 Ct/KWh
electricity	fossils	$dy_{dA} > 0$	?	$dy_{dA} < 0$	20.3	14.4	−99.2	82.4 TWh	58.6 TWh	−403 TWh
generation	renewables	$dy_{cA} > 0$	$dy_{cA} > 0$	$dy_{cA} > 0$	6.5	5.3	15.6	118.7 TWh	96.6 TWh	286 TWh
COA	fos + ren	+	?	?	9	6.9	−5.2	201 TWh	155 TWh	−117 TWh
electricity	fossils	$dy_{dj} < 0$	?	$dy_{dj} < 0$	−9.3	−3	−93.6	−24.5 TWh	−7.9 TWh	−247 TWh
generation	renewables	$dy_{cj} > 0$	$dy_{cj} > 0$	$dy_{cj} > 0$	4.6	7.9	41.8	14.1 TWh	24.1 TWh	127 TWh
NCOA	fos + ren	−	?	?	−1.8	2.8	−21	−10.4 TWh	16.1 TWh	−119 TWh
electricity gen.	fos + ren	+	+	−	6.8	6.1	−8.4	191 TWh	171 TWh	−236 TWh

* Unilateral tax of COA regions (tax of NCOA regions is 0).

for the unilateral tax, whose direct effects are restricted to the OEC sectors in COA, this strong negative impact on emissions in the ETS sectors of the other region — the "reverse waterbed effect" — is intriguing. As shown in the theoretical analysis, it arises mainly from the combined effects of linkage across sectors via sector coupling and linkage across countries via the ETS. Moreover, also total emissions in NCOA fall, although its OEC sectors gain comparative advantage from not participating in COA's unilateral policies, which in the absence of sector coupling should tend to raise emissions. Intuitively, total emission reductions are much more balanced across the two regions under the cancellation of ETS II allowances as it affects them symmetrically. For *tax-OEC*, reductions are −18.9% for COA and −3.2% for NCOA, whereas for *kill-OEC* they are −15.2% for COA and −14.2% for NCOA.

So far the discussion has focused on the *tax-OEC* and *kill-OEC* scenarios for which the unilateral action takes place in the OEC sectors. By contrast, under *kill-ETS,* coalition countries unilaterally cancel allowances of the EU ETS. Hence the main effects take place in this sector, leading to a substantial increase in the ETS price by 85.1 $\$/tCO_2$. This results in a nearly complete phase-out of electricity generation from fossils in both regions (−99.2% in COA and −93.6% in NCOA). Moreover, electricity prices rise substantially more than with the two OEC sector policies,[10] which makes sector-coupling technologies more expensive. As a result, electricity demand falls so that total electricity generation decreases significantly for both COA and NCOA (by −8.4% in total). This outcome of *kill-ETS* contrasts sharply with the two unilateral policies in the OEC sectors that foster sector coupling and, thus, imply a higher total electricity generation (+6.8 under *tax-OEC* and +6.1% under *kill-OEC*).

3.4 Numerical results: Welfare effects

Beyond the specific implications for emissions and electricity markets that we related to our theoretical analysis, the CGE simulations provide insights into the economy-wide adjustment cost of our different climate policy scenarios. We report them in terms of a standard welfare metric, the Hicksian equivalent variation (HEV) in income. Given that all scenarios achieve an identical level of EU-wide emissions reductions, we obtain a coherent cost-effectiveness comparison for them.

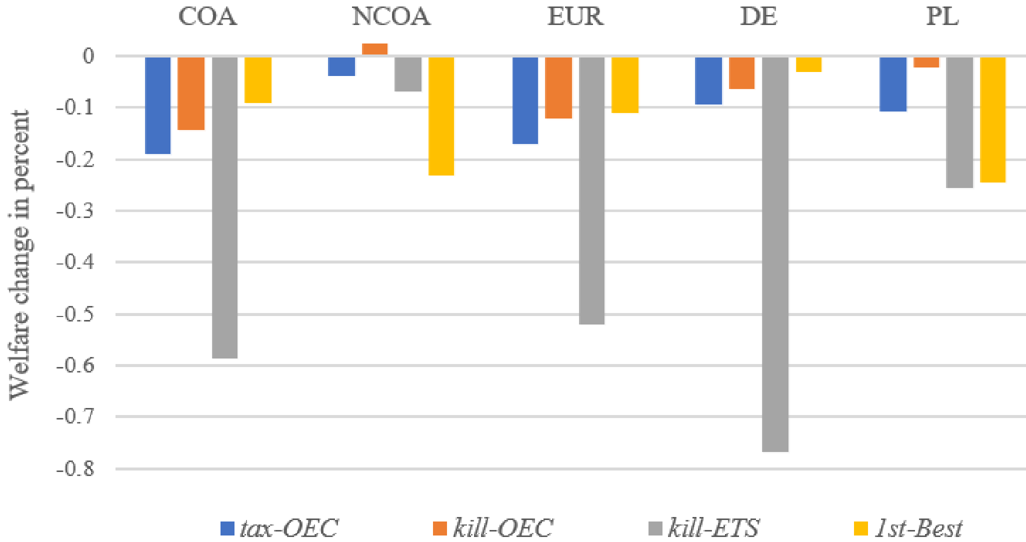
Figure 2 reports the welfare effects of these policy options for the aggregates of coalition (COA) and non-coalition (NCOA) countries, for Germany (DE) and Poland (PL) as selected countries from these two groups, as well as for the EU-wide aggregate (EUR). The first two bars compare the two OEC policies, the third bar the alternative ETS policy. Note that our welfare metric does not include the monetarized environmental benefits of lower emissions. Therefore, welfare effects are always negative, even in the first-best solution (last bar) that has the same overall emission reductions as the other scenarios, but assumes a common CO_2 price across all EU sectors and countries.

For all regions, the two unilateral policies in the OEC sectors lead to substantially lower welfare losses than the unilateral cancellation of allowances in the ETS for the power sector. This reflects that under *kill-ETS* both cooperative and unilateral allowance reductions take only place in the ETS sector, whereas under *tax-OEC* and *kill-OEC* emission reductions are distributed over both sectors, thereby exploiting benefits from where-flexibility. The countries that unilaterally cancel allowances bear most of these costs, which explains that COA's welfare losses are particularly high under *kill-ETS*, and even more so in Germany.

Of the two OEC policies, EU-wide welfare losses are lower under *kill-OEC* because cancelling allowances secures a common allowance price across all OEC sectors in the EU. As Figure 2 shows, all regions benefit from efficiency gains under *kill-OEC* as compared to *kill-TAX*. For the composite of NCOA and Poland this may appear surprising at first glance as *kill-OEC* induces them to make much larger emission reductions than *tax-OEC* (−14.2% versus −3.2% for NCOA, see Table 3). However, NCOA and Poland only implement these reductions because their revenues from selling emission allowances exceed the associated abatement costs. Under *tax-OEC* these gains are missing, and emission

[10] These prices are country-specific and in Table 3 we have reported them for Germany and EEC.

Fig. 2: Welfare effects of policy scenarios (% HEV from scenario *ref*, without benefits of emission reductions)



reductions of NCOA mainly result from the reverse waterbed effect in the ETS sector, where its emissions fall by 6.9%. In particular, the electrification of the OEC sectors shifts some emission reductions and associated costs to the power sector, as reflected in the higher ETS allowance price (see Table 3). Due to their high share of fossils in electricity production, NCOA and Poland suffer most from this. In conclusion, direct and indirect effects of the policy instruments, as well as the questions of who reduces emissions and who bears the associated welfare costs, must be carefully separated.

4 Concluding remarks

It is widely acknowledged that a uniform CO_2 price would be desirable for reducing CO_2 emissions in a cost-effective manner. However, real world policies are often fragmented and include a plethora of measures with different CO_2 prices across sectors and jurisdictions, as well as heterogeneous subsidy schemes. The payments involved are enormous. For example, over the next decade, the US Inflation Reduction Act directs nearly $400 billion in federal funding to reduce carbon emissions, the EU budget provides €503 billion for climate and environmental spending, and revenues from auctioning EU-ETS allowances have been €25 billion in 2021 alone.[11] Economists have pointed out potential problems of overlapping regulations, especially for sectors that are covered by an emissions trading system (ETS) . With a fixed cap, overlapping policies in this sector — like subsidies for renewables or a coal phaseout — cannot affect its emissions by construction, but imply a dilution of the ETS. This is often captured with the analogy of a waterbed effect, where avoided emissions pop up elsewhere. More specifically, if such overlapping policies are implemented unilaterally, the burden of emission reductions in the other regions falls.

By contrast, in this paper we have focused on the interaction of an ETS covering the electricity sector with complementary measures in the other energy consuming (OEC) sectors. These sectors are closely linked as decarbonising the OEC sectors ultimately requires the electrification of all energy-related processes, so-called sector coupling. Examples include the switch to BEVs in the transport

[11] See https://www.crfb.org/blogs/cbo-scores-ira-238-billion-deficit-reduction on the Inflation Reduction Act, EC COM(2020) 21 final on the EU's Sustainable Europe and European Green Deal Investment Plans, and https://www.eea.europa.eu/data-and-maps/daviz/auctioning-revenues-and-reported-usage/#tab-chart_2 for data on revenues from auctioning EU-ETS allowances.

sector, to heat pumps in the buildings sector, and to green hydrogen in the industrial sector, all of which feature very prominently in current policy debates. Using a simple multi-region two-sector analytical model that captures sector coupling by treating the output of the electricity sector as an input in the OEC sector, we have shown that policies promoting such power-to-X technologies lead to a "reverse waterbed effect". In particular, the additional electricity demand implies a tightening of the ETS as less emissions are left for the other activities covered by it. Moreover, if policies that foster electrification of the OEC sectors are taken unilaterally, some of the emissions from additional electricity generation are taken from the other countries' side of the waterbed. Thus, also their burden of emission reductions rises.

The paramount relevance of power-to-X technologies and their cross-sectoral effects also have implications for the sectoral targeting of policies. We have shown this to be the case for the cancellation of allowances, which can alternatively be implemented in the ETS or OEC sectors (provided, that the latter is also governed by a cap-and-trade system). Specifically, many countries aim to increase the share of renewable energies as well as that of BEVs. Cancelling ETS allowances achieves the first goal, but — by rising electricity prices — negatively impacts the second. By contrast, cancelling allowances in the OEC sectors supports both goals. Of course, a mix of both would usually be the best option, but even then the effects from sector coupling need to be carefully taken into account. Not only in policy discussions, but also in the economics literature, this happens too rarely so far.

The relevance of sector coupling for an assessment of emission reduction policies is by no means restricted to the cases that we considered in this paper. For example, even though support policies for renewable energies are largely ineffective for reducing emissions in the ETS sector, they lower the allowance price and, thus, also the electricity price. This reduces emissions in the OEC sectors because power-to-X technologies such as BEVs and heat pumps become cheaper. Moreover, the cross-sectoral effects of power-to-X technologies are also relevant if countries choose other instruments than cap-and-trade, e.g., environmental performance standards or CO_2 taxes. For example, the tax that is needed to achieve a certain emissions reduction target in the electricity sector rises if power-to-X technologies are subsidised. Thus, the economics of sector coupling lead to a large research agenda waiting to be addressed.

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A Appendix: Proofs of propositions in analytical model

We start by deriving some expressions that are used in the proofs of all propositions. 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 cost for all sectors and technologies in $i \in N$:

$$
\begin{aligned}
u_i'(y_i) &= C_{di}'(y_{di}) + \nu\alpha_y, && (15)\\
u_i'(y_i) &= C_{ci}'(y_{ci}), && (16)\\
u_i'(x_i) &= C_{di}'(x_{di}) + (\tau_i + \varphi)\,\alpha_x, && (17)\\
u_i'(x_i) &= C_{ci}'(x_{ci}) + \beta C_{ci}'(y_{ci}) - \sigma_i, && (18)
\end{aligned}
$$

where we have used $C_{ci}'(y_{ci}) = p_{yi}$ (from Eq. 6) in the last line. Intuitively, marginal costs of clean transport include marginal electricity costs. Total differentiation of these expressions yields

$$
u_i''(y_i)dy_i = C_{di}''(y_{di})dy_{di} + \alpha_y d\nu, \qquad (19)
$$

$$
\begin{aligned}
u_i''(y_i)dy_i &= C_{ci}''(y_{ci})dy_{ci}, && (20)\\
u_i''(x_i)dx_i &= C_{di}''(x_{di})dx_{di} + \alpha_x\left(d\tau_i + d\varphi\right), && (21)\\
u_i''(x_i)dx_i &= C_{ci}''(x_{ci})dx_{ci} + \beta C_{ci}''(y_{ci})dy_{ci} - d\sigma_i. && (22)
\end{aligned}
$$

Moreover, total differentiation of the market clearing conditions (13) and (14) for x_i and y_i, as well as condition (11) for the allowance market in the ETS sectors yields

$$dx_i = dx_{di} + dx_{ci} \quad \text{and} \quad dy_i = dy_{di} + dy_{ci} - \beta dx_{ci},\ i \in N, \tag{23}$$

$$\sum_{i\in N} \alpha_y dy_{di} = 0. \tag{24}$$

The proofs are based on evaluating this system of equations (19) to (24) that determines the comparative static effects of the policy intervention on the endogenous variables (if there is an ETS II, there will be an additional market clearance condition). In doing so, we will repeatedly use the following relations. Due to strict concavity of utility and strict convexity of the cost functions, we have $u_i''(\cdot) < 0$ and $C_{ci}''(\cdot), C_{di}''(\cdot) > 0$ so that (20) immediately implies

$$\text{sign}(dy_{ci}) = -\text{sign}(dy_i) \ \text{ for all } \ i \in N. \tag{25}$$

Moreover, using (24), summation of (23) yields the following aggregate effects:

$$\sum_{i\in N} dx_i = \sum_{i\in N} dx_{di} + \sum_{i\in N} dx_{ci} \quad \text{and} \quad \sum_{i\in N} dy_i = \sum_{i\in N} dy_{ci} - \beta \sum_{i\in N} dx_{ci},\ i \in N. \tag{26}$$

A.1 Proof of Proposition 1

The comparative static effects in the proposition must satisfy the equations system (19) to (24) for $d\varphi = 0$, as well as either $d\tau_A > d\tau_j = 0$ (unilateral tax) or $d\sigma_A > d\sigma_j = 0$ (unilateral subsidy), where $j \in N\backslash A$. By contradiction to statement (a), suppose $d\nu \leq 0$. Using (24) we either have (i) $dy_{dA} \leq 0$ and there is at least one country $j \in N\backslash A$, denoted B, for which $dy_{dB} \geq 0$, or (ii) $dy_{dA} > 0$ and there is at least one country $j \in N\backslash A$ for which $dy_{dB} < 0$. From (19), case (ii) implies $dy_B > 0$ so that $dy_{cB} < 0$ (from 25). Hence (23) can only be satisfied if $dx_{cB} < 0$. Noting that $d\sigma_B = d\tau_B = 0$, from (22) and $u_i''(x_i) < 0$ we obtain $dx_B > 0$ so that $dx_{dB} < 0$ (from 21). However, using $dx_{cB} < 0$ this cannot satisfy (23); hence we have a contradiction.

Turning to the alternative case (i), $dy_{dA} \leq 0$ implies $dy_A \geq 0 \Longrightarrow dy_{cA} \leq 0$ (from 19). Hence $dx_{cA} \leq 0$ (from 23) so that $dx_A \geq 0$, where the inequality is strict for the subsidy case with $d\sigma_A > 0$. Therefore, condition (21) can only be satisfied if $dx_{dA} < 0$, where in the tax case the strict inequality follows from $d\tau_A > 0$. However, these results cannot satisfy (23). Hence also case (i) leads to a contradiction and we conclude that $d\nu > 0$.

Next, by contradiction to statement (c), suppose that there is a country $j \in N\backslash A$, denoted B, for which $dy_{dB} \geq 0$. From (19) and $d\nu > 0$ we then have $dy_B < 0 \Longrightarrow dy_{cB} > 0$ so that $dx_{cB} > 0$ (from 23) and $dx_B < 0$ (from 22). This in turn implies $dx_{dB} > 0$ (from 21) so that (23) is violated. Hence we conclude that $dy_{dj} < 0\ \forall\ j \in N\backslash A$ which from (24) immediately implies $dy_{dA} > 0$.

Using $d\nu > 0$ and $dy_{dA} > 0$, it follows from (19) that $dy_A < 0 \Longrightarrow dy_{cA} > 0$, which in turn requires $dx_{cA} > 0$ to satisfy (23). For the tax instrument (i.e., for $d\sigma_A = 0$), this implies $dx_A < 0$, which requires $dx_{dA} < 0$. Turning to the subsidy instrument, suppose that $dx_A \leq 0$. Using $d\tau_A = 0$ this implies $dx_{dA} \geq 0$ (from 21), which cannot satisfy (23). Hence we have a contradiction and conclude that $dx_A > 0$, which implies $dx_{dA} < 0$ (from 21).

We now turn to countries $j \in N\backslash A$ for which $d\tau_j, d\sigma_j = 0$. By contradiction to statement (c), suppose that $dy_j \geq 0 \Longrightarrow dy_{cj} \leq 0$. Using $dy_{dj} < 0$, (23) requires $dx_{cj} < 0$ so that $dx_j > 0$ (from 22) and $dx_{dj} < 0$ (from 21), which cannot satisfy (23). Hence we conclude that $dy_j < 0 \Longrightarrow dy_{cj} > 0\ \forall\ j \in N\backslash A$. Next, consider the OEC sector and suppose by contradiction that $dx_j \geq 0$. Then $dx_{dj} \leq 0$ from

(21) and $dx_{cj} < 0$ (from (22) and $dy_{cj} > 0$), which cannot satisfy (23). Therefore, $dx_j < 0$, which implies $dx_{dj} > 0$ (from 21) so that $dx_{cj} < 0$ (from 23).

Finally, total differentiation of (9) and (10) immediately shows that the effects on prices dp_{yi} and dp_{xi} always have the opposite sign of dy_i and dx_i.

A.2 Proof of Proposition 2

Statement (a) has already been shown in the paragraphs before the proposition. Turning to (b), from Proposition 1, $\sum_{i\in N} dy_i < 0$ and $\sum_{i\in N} dy_{ci} > 0$ so that (26) implies $\sum_{i\in N} dx_{ci} > 0$. In the case of a tax, $dx_i = dx_{di} + dx_{ci} < 0$ (from Proposition 1) and, thus, $dx_{di} < -dx_{ci}$ for *all* $i \in N$. Adding up this expression and using $\sum_{i\in N} dx_{ci} > 0$ yields $\sum_{i\in N} dx_{di} < -\sum_{i\in N} dx_{ci} < 0$ so that $de = \alpha_x \sum_{i\in N} dx_{di} < 0$. Note that this argument does not extend to the case of a subsidy because the sign of $\sum_{i\in N} dx_i < 0$ is ambiguous.

A.3 Proof of Proposition 3

If there is also an ETS in the OEC sector, we have a further market clearance condition for that allowance market:

$$\alpha_x \sum_{i\in N} dx_{di} = -\zeta. \tag{27}$$

Otherwise, the comparative static effects follow again from the system of equations (19) to (24) after setting $d\tau_i = d\sigma_i = 0 \;\forall\; i \in N$.

By contradiction to the proposition, assume $d\varphi \leq 0$ and note that due to the cancellation of allowances in the ETS II there must be countries (at least one), indexed j, for which $dx_{dj} < 0$. For them, $dx_j > 0$ from (21) so that $dx_{cj} > 0$ from (23). Using this, (22) requires $dy_{cj} < 0$ so that $dy_j > 0$ from (25). Hence $dy_{dj} > 0$ from (23) and $d\nu < 0$ from (19).

By construction, for all other countries, indexed k, we have $dx_{dk} \geq 0$. Moreover, suppose that such a country has $dy_k \leq 0 \Longrightarrow dy_{ck} \geq 0$ so that $dy_{dk} > 0$ from (19) and, thus, $dy_{di} > 0$ for all $i \in N$. This violates (24) so that we must have $dy_k > 0 \Longrightarrow dy_{ck} < 0 \,\forall\, k$. Noting that the signs are the same as for j-type countries, $\sum_{i\in N} dy_i > 0$ and $\sum_{i\in N} dy_{ci} < 0$. From (26) this implies $\sum_{i\in N} dx_{ci} < 0$ and, thus, $\sum_{i\in N} dx_i < 0$. Moreover, there can be no k-type country with $dx_k \leq 0$ as this would imply $dx_{ck} > 0$ (from 22), which violates (23). Hence $dx_k > 0 \,\forall\, k$ and, thus, $\sum_{i\in N} dx_i > 0$. This yields a contradiction and we conclude that $d\varphi > 0$.

As before, let k be the index for countries with $dx_{dk} \geq 0$ and assume, by contradiction, that such countries exist. Using $d\varphi > 0$, for all such countries we obtain $dx_k < 0$ (from 21), $dx_{ck} < 0$ (from 23), $dy_{ck} > 0 \Longrightarrow dy_k < 0$ from (22), $dy_{dk} < 0$ (from 23), and, thus, $d\nu > 0$ from (19). From the fixed allowance endowment in the ETS, at least one of the other countries (indexed j and characterized by $dx_{dj} < 0$) must have $dy_{dj} > 0$ so that $dy_j < 0 \Longrightarrow dy_{cj} > 0$ (from 19). It follows that $dx_{cj} > 0$ (from 23) and $dx_j < 0$ (from 22).

Note that all countries have the common terms $\alpha_y d\nu$ and $\alpha_x d\varphi$. Hence subtraction of the FOCs (19) for countries of types j and k, and doing the same with (20) yields

$$u_j''(y_j)dy_j - u_k''(y_k)dy_k = C_{dj}''(y_{dj})dy_{dj} - C_{dk}''(y_{dk})dy_{dk} = C_{cj}''(y_{cj})dy_{cj} - C_{ck}''(y_{ck})dy_{ck} > 0, \tag{28}$$

where the sign follows from $dy_{dj} > 0$ and $dy_{dk} < 0$. Similarly, subtraction of the FOCs (21) and (22) for countries of types j and k yields

$$C_{dj}''(x_{dj})dx_{dj} - C_{dk}''(x_{dk})dx_{dk} = C_{cj}''(x_{cj})dx_{cj} + \beta C_{cj}''(y_{cj})dy_{cj} - C_{ck}''(x_{ck})dx_{ck} - \beta C_{ck}''(y_{ck})dy_{ck} < 0, \tag{29}$$

where the sign follows from $dx_{dj} < 0$ and $dx_{dk} \geq 0$. Noting the sign of the two terms on the right-hand side of (28), the sign of (29) requires that $C_{cj}''(x_{cj})dx_{cj} - C_{ck}''(x_{ck})dx_{ck} < 0$, which is inconsistent with our previous results that $dx_{ck} < 0$ and $dx_{cj} > 0$. Hence we have a contradiction and conclude that $dx_{di} < 0$ for all $i \in N$.

In the remainder of the proof, we use index j for countries with $dy_{dj} < 0$ and k for $dy_{dk} \geq 0$. By contradiction to the proposition, suppose that $\nu \leq 0$. From (19) we obtain $dy_j \geq 0 \Longrightarrow dy_{cj} \leq 0$ so that $dx_{cj} < 0$ (from 23), which in turn implies $dx_j > 0$ (from 22) and $dx_j < 0$ (from 23), a contradiction. We conclude that $\nu > 0$.

Using this and $dy_{dk} \geq 0$ for k-type countries, $dy_k < 0 \Longrightarrow dy_{ck} > 0$ (from 19) so that $dx_{ck} > 0$ (from 23) and, thus, $dx_k < 0$ (from 22). By contrast, from (19) countries with $dy_{dj} < 0$ could have $dy_j \geq 0$. However, we have shown in the preceding paragraph that this constellation leads to a contradiction. Hence we conclude that $dy_i < 0 \Longrightarrow dy_{ci} > 0$ for all $i \in N$. Moreover, suppose there were a j-type country with $dx_j \geq 0$. Then $dx_{cj} < 0$ (from 22) so that $dx_j < 0$ from (23), a contradiction. We conclude that $dx_i < 0$ for all $i \in N$. Finally, note that neither (22) nor the two expressions in (23) allow us to fix the sign of dx_{cj}. Nevertheless, $\sum_{i \in N} dx_{ci} > 0$ (from 26).

A.4 Proof of Proposition 4

If ρ allowances are cancelled in the ETS, total differentiation of the market clearance condition for that allowance market yields

$$\alpha_y \sum_{i \in N} dy_{di} = -\rho. \tag{30}$$

Moreover, using this and the fixed allowance endowment in the ETS II for the OEC sector, condition (26) changes to

$$\sum_{i \in N} dx_i = \sum_{i \in N} dx_{ci} \quad \text{and} \quad \sum_{i \in N} dy_i = \sum_{i \in N} dy_{di} + \sum_{i \in N} dy_{ci} - \beta \sum_{i \in N} dx_{ci},\ i \in N. \tag{31}$$

The result $d\varphi > 0$ follows from the same steps as in the beginning of the proof of Proposition 3, except that we use (30) and (31) instead of the corresponding conditions (24) and (26). Next, as in that proof let k be the index for countries with $dx_{dk} \geq 0$ and note that such countries exist due to the fixed allowance endowment in the ETS II. Using $d\varphi > 0$, for all such countries we obtain $dx_k < 0$ from (21), $dx_{ck} < 0$ from (23), $dy_{ck} > 0 \Longrightarrow dy_k < 0$ from (22), $dy_{dk} < 0$ from (23), and, thus, $d\nu > 0$ from (19).

Turning to j-type countries (characterized by $dx_{dj} < 0$), by contradiction assume that there is one with $dy_{dj} \geq 0$. Note that expressions (28) and (29) still hold as they are based on the same classification of j-type and k-type countries according to $dx_{dk} \geq 0$ and $dx_{dj} < 0$. This classification immediately implies that (29) is still strictly negative. Moreover, we have already shown that $dy_{dk} < 0$; hence assuming $dy_{dj} \geq 0$ expression (28) is still strictly positive, which (using $dy_{ck} > 0$) requires that $dy_{cj} > 0 \Longrightarrow dy_j < 0$. Noting the sign of the two terms on the right-hand side of (28), the sign of (29) requires that $C''_{cj}(x_{cj})dx_{cj} - C''_{ck}(x_{ck})dx_{ck} < 0$. Using $dx_{ck} < 0$, this requires that $dx_{cj} < 0$. Together with $dy_{dj} \geq 0, dy_{cj} > 0$, and $dy_j < 0$ this violates (23). Hence we have a contradiction and conclude that $dy_{di} < 0$ for all $i \in N$.

Next, by contradiction suppose that we have a j-type country with $dy_{cj} \leq 0 \Longrightarrow dy_j > 0$. From (23) this requires $dx_{cj} < 0$ so that (23) implies $dx_j < 0$, whereas (22) implies $dx_j > 0$. Hence we have a contradiction and conclude that $dy_{ci} > 0 \Longrightarrow dy_i < 0$ for all $i \in N$.

Turning to the aggregate effects, remember that we have already shown that $dx_k, dx_{ck} < 0$ for all k-type countries. From (23) and $dx_{dj} < 0$, j-type countries with $dx_{cj} < 0$ also have $dx_j < 0$. However, a priori there can likewise be j-type countries with $dx_{cj} \geq 0$. Using $dy_{cj} > 0$ and (22), also for them $dx_j < 0$. We conclude that $dx_i < 0$ for all $i \in N$, which from (31) implies that $\sum_{i \in N} dx_{ci} < 0$. Finally, using this and $dy_i < 0 \ \forall \ i \in N$, rearranging (31) yields $\sum_{i \in N}(dy_{di} + dy_{ci}) = \sum_{i \in N}(dy_i + \beta dx_{ci}) < 0$.

B Computable General Equilibrium model

For our numerical analysis we use a standard multi-sector multi-region computable general equilibrium (CGE) model. In section 3.1 we laid out the non-standard extensions towards the discrete representation of alternative power generation technologies and direct substitution possibilities of fossil fuel demands by electricity. Below, we provide a non-technical summary of all other basic model features followed by an algebraic description of the generic model.

B.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 labour 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 and power-to-X technologies for the direct substitution of fossil fuels in intermediate and final demands. Factor markets are perfectly competitive.

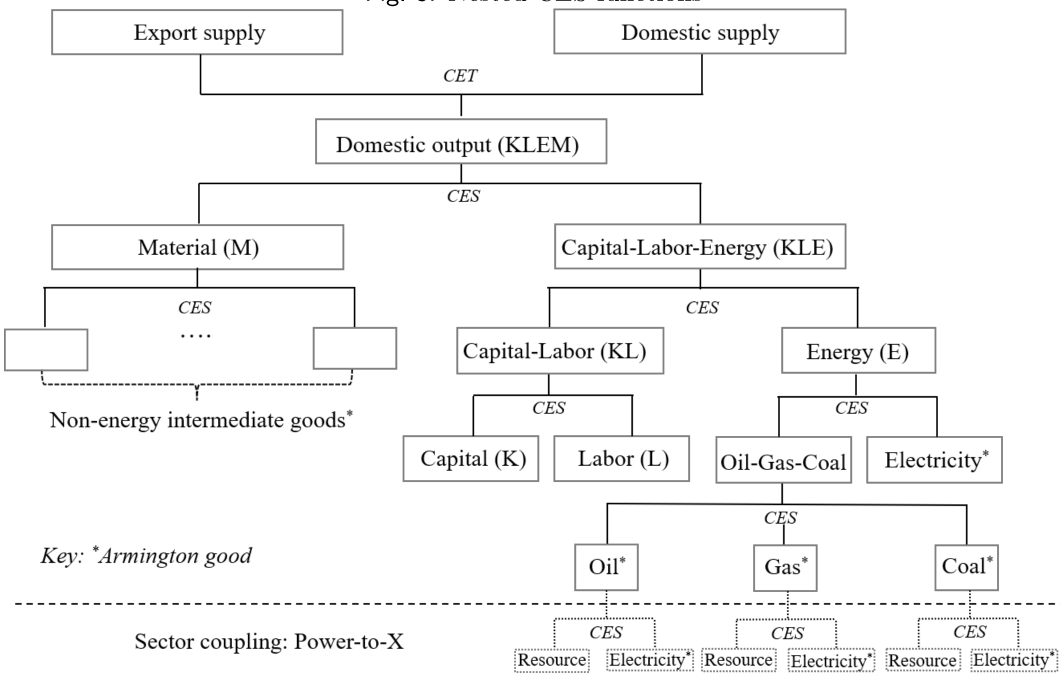
Figure 3 visualizes the trade-offs between inputs to the production of commodities at constant elasticities of substitution (CES). All commodities except for fossil fuels and electricity are produced according to nested CES functions combining inputs of capital (K), labour (L), energy (E), and material (M). At the top level, a material composite (M) trades off with an aggregate of capital, labour, and energy (KLE). At the second level, the material composite splits into non-energy intermediate goods, whereas the aggregate of capital, labour, and energy splits into a value-added composite (KL) and the energy component (E). At the third level, capital and labour inputs enter the value-added composite subject to a constant elasticity of substitution. Likewise, within the energy aggregate, electricity trades off with a 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 where each fossil fuel has a specific CO_2 coefficient. Finally, there is the possibility to substitute oil, gas, and coal demands directly by electricity — the latter is combined with a fixed specific resource to feature decreasing returns to scale and render an upward sloping supply curve. On the output side, production is allocated either to the domestic market or the export market subject to a constant elasticity of transformation.

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 fossil fuel 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.

Household consumption stems from a representative agent in each region who receives income from primary factors and maximizes welfare subject to a budget constraint. 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. Substitution patterns in private consumption as well as in the composition of the investment and public goods are described through nested CES functions according to Figure 3.

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: (*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

Fig. 3: Nested CES functions



deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of CO_2 emissions in production and consumption are implemented through exogenous emissions constraints (e.g in case of the EU ETS as a multilateral cap-and-trade system on emissions from the ETS sectors across all EU member states) or CO_2 taxes. CO_2 emissions abatement takes place via fuel switching (interfuel substitution including power-to-X) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).

B.2 Algebraic model summary

Our CGE model is stated as a mixed complementarity problem (MCP) which links equilibrium conditions as non-linear inequalities with complementary non-negative economic variables. The fundamental advantage of implementing equilibrium conditions as an MCP (rather than a system of non-linear equations) is the ability to handle corner solutions and regime shifts, thereby capturing sorting decisions across alternative possibilities to produce the same commodity based on relative profitability.

The inequalities correspond to the three fundamental classes of conditions associated with an economic equilibrium: zero-profit conditions for all economic activities, market-clearance conditions for all commodities and factors, and income-expenditure balances for consumers. Complementary to the equilibrium conditions are three classes of economic decision variables: activity levels, prices for commodities and factors, and income levels. In equilibrium, each of these variables is linked to the respective inequality condition: an activity level to a zero-profit condition, a price to a market-clearance condition, and an income level to an income-expenditure balance.

We use the notation Π^u_{ir} to denote the profit function of sector i in region r, where superscript u denotes the associated production activity. We apply Hotelling's lemma to represent compensated demand and supply functions, and we express the cost functions in calibrated share form. The notations used are summarized in Table 4. Note that in the algebraic exposition below we abstain for the sake of compactness from an explicit representation of fiscal flows (except for CO_2 revenues) as well as discrete alternative power technologies and sector coupling technologies.

B.2.1 Zero-profit conditions

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

$$\begin{aligned}\Pi^Y_{ir} \;=\; & \left(\theta^D_{ir} p^{D\,1+\eta_{ir}}_{ir} + \left(1-\theta^D_{ir}\right) p^{X\,1+\eta_{ir}}_{ir}\right)^{\frac{1}{1+\eta_{ir}}} - \left\{\left(\sum_{j\notin EG} \theta_{jir} p^A_{jr}\right)^{1-\sigma^{KLEM}_{ir}} - \theta^{KLE}_{ir}\left[(1-\theta^{KL}_{ir})\right.\right. \\ & \left.\left. p^{E\,1-\sigma^{KLE}_{ir}}_{ir} + \theta^{KL}_{ir}\left(\theta^L_{ir} p^{L\,1-\sigma^{KL}_{ir}}_r + (1-\theta^L_{ir}) p^{K\,1-\sigma^{KL}_{ir}}_r\right)^{\frac{1-\sigma^{KLE}_{ir}}{1-\sigma^{KL}_{ir}}}\right]^{\frac{1-\sigma^{KLEM}_{ir}}{1-\sigma^{KLE}_{ir}}}\right\}^{\frac{1}{1-\sigma^{KLEM}_{ir}}} \le 0\end{aligned}$$

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

$$\begin{aligned}\Pi^Y_{ir} \;=\; & \left(\theta^D_{ir} p^{D\,1+\eta_{ir}}_{ir} + \left(1-\theta^D_{ir}\right) p^{X\,1+\eta_{ir}}_{ir}\right)^{\frac{1}{1+\eta_{ir}}} - \left[\theta^Q_{ir} p^{Q\,1-\sigma^Q_{ir}}_{ir}\right. \\ & \left. +(1-\theta^Q_{ir})\left(\theta^{FF}_{Lir} p^L_r + \theta^{FF}_{Kir} p^K_r + \sum_j \theta^{FF}_{jir}\left(p^A_{ir} + p^{CO_2}_r a^{CO_2}_j\right)\right)^{1-\sigma^Q_{ir}}\right]^{\frac{1}{1-\sigma^Q_{ir}}} \le 0\end{aligned}$$

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

$$\Pi^E_{ir} = p^E_{ir} - \left\{\theta^E_{ELEir} p^{A\;1-\sigma^{ELE}_{ir}}_{ELEr} - \left(1-\theta^E_{ELEir}\right)\left(\sum_{j\in FE} \theta^{FE}_{jir}\left(p^A_{jr} + p^{CO_2}_r a^{CO_2}_j\right)^{1-\sigma^{FE}_{ir}}\right)^{\frac{1-\sigma^{ELE}_{ir}}{1-\sigma^{FE}_{ir}}}\right\}^{\frac{1}{1-\sigma^{ELE}_{ir}}} \le 0$$

3. Armington aggregate

$$\Pi^A_{ir} = p^A_{ir} - \left(\theta^A_{ir} p^{D\,1-\sigma^A_{ir}}_{ir} + (1-\theta^A_{ir}) p^{M\,1-\sigma^A_{ir}}_{ir}\right)^{\frac{1}{1-\sigma^A_{ir}}} \le 0$$

4. Import aggregate

$$\Pi^M_{ir} = p^M_{ir} - \left(\sum_{s\neq r} \theta^M_{isr} p^{X\,1-\sigma^M_{ir}}_{is}\right)^{\frac{1}{1-\sigma^M_{ir}}} \le 0$$

B.2.2 Market-clearance conditions[12]

5. Labor

$$\overline{L}_r \ge \sum_{ir} Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^L_r}$$

6. Capital

$$\overline{K}_r \ge \sum_{ir} Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^K_r}$$

7. Specific fossil fuel resources ($i \in FF$)

$$\overline{Q}_{ir} \ge Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^Q_{ir}}$$

[12] Note that market-clearance conditions are oriented with supplies on the left-hand side and demands on the right-hand side. Hence, in equilibrium should the price of a good be zero, economic equilibrium is then consistent with a market in which *supply > demand.*

8. Domestic production

$$Y_{ir} \geq DX_{ir} \frac{\partial \Pi_{ir}^{DX}}{\partial p_{ir}^{Y}}$$

9. Domestic supply

$$Y_{ir} \frac{\Pi_{ir}^{Y}}{\partial p_{ir}^{D}} \geq \sum_{j} A_{jr} \frac{\Pi_{jr}^{A}}{\partial p_{ir}^{D}}$$

10. Export supply

$$Y_{ir} \frac{\Pi_{ir}^{Y}}{\partial p_{ir}^{X}} \geq \sum_{s} M_{is} \frac{\Pi_{is}^{M}}{\partial p_{ir}^{X}}$$

11. Armington aggregate

$$A_{ir} \geq \sum_{j} Y_{jr} \frac{\Pi_{jr}^{Y}}{\partial p_{ir}^{A}}$$

12. Import aggregate

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

13. Sector-specific energy aggregate

$$E_{ir} \geq Y_{ir} \frac{\Pi_{ir}^{Y}}{\partial p_{ir}^{E}}$$

14. Private Consumption ($i = C$)

$$p_{Cr} Y_{Cr} \geq \Upsilon_r$$

15. Public consumption ($i = G$)

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

16. Investment ($i = I$)

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

17. CO_2 emissions

$$\overline{CO2}_r \geq \sum_{ir} Y_{ir} \frac{\Pi_{ir}^{Y}}{\partial p_{r}^{CO_2}}$$

B.2.3 Income-expenditure balance

18. Income balance of the representative agent (household)[13]

$$\Upsilon_r = p_r^L \overline{L} + p_r^K \overline{K} + \sum_{j \in FF} p_r^Q \overline{Q}_j + -p_{Cr_n}^Y \overline{B}_r + p_r^{CO_2} \overline{CO2}_r - p_{Ir}^Y \overline{I}_r - p_{Gr}^Y \overline{G}_r$$

[13] We denote the balance of payment $\overline{B}_r$ for each region r in terms of the final consumption price index of a numeraire region with subscript n. Note that across all regions balance of payment deficits or surpluses add up to zero such that aggregate term drops out from the market clearance condition of the composite consumption in the numeraire region.

Tab. 4: Notations for variables

	Sets and indexes
i, j	Indexes for commodities (sectors) and goods
r, s	Indexes for commodities (sectors) and goods
u	Index (superscript) in profit function to denote the respective production activity
EG	All energy goods: Coal, crude oil, natural gas, refined oil, and electricity
FE	Secondary energy goods with CO_2 emissions: Coal, natural gas, refined oil
FF	Primary fossil fuels: Coal, crude oil, natural gas
	Activity variables
Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy demand by sector i and region r
A_{ir}	Armington aggregate of good i in region r
M_{ir}	Import composite of good i in region r
Υ_r	Disposable household income in region r
	Price variables
p^D_{ir}	Domestic supply price of good i in region r
p^X_{ir}	Export supply price of good i from region r
p^E_{ir}	Price of energy aggregate in sector i and region r
p^A_{ir}	Price of Armington good i in region r
p^M_{ir}	Price of import composite for good i in region r
p^L_r	Wage rate in region r
p^K_r	Capital rent in region r
p^Q_{ir}	Resource rent to specific fossil fuel resources in sector i ($i \in FF$) and region r
p^{CO_2}	CO_2 emissions price in region r
	Cost shares of ...
θ_{jir}	Intermediate good j in sector i and region r
θ^{KLE}_{ir}	Capital-labor-energy (KLE) composite in sector i and region r
θ^{KL}_{ir}	Capital-labor composite in the KLE composite of sector i ($i \notin FF$) in region r
θ^L_{ir}	Labor in the capital-labor composite of sector i in region r
θ^Q_{ir}	Fossil fuel resources in sector i ($i \in FF$) and region r
θ^{FF}_{Tir}	Good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in the aggregate non-resource inputs to sector i ($i \in FF$) of region r
θ^E_{ELEir}	Electricity in the energy composite of sector i and region r
θ^{FE}_{jir}	Secondary energy good j ($j \in FE$) in the energy composite of sector i and region r
θ^A_{ir}	Domestic supply in Armington good i of region r
θ^M_{isr}	Imports of good i from region s to region r
θ^D_{ir}	Value share of domestic supply in production of good i in region r
	Substitution elasticities between ...
σ^{KLEM}_{ir}	KLE composite and material inputs in sector i and region r
σ^{KLE}_{ir}	Energy and value-added in sector i and region r
σ^{KL}_{ir}	Labor and capital in the value-added composite of sector i and region r
σ^Q_{ir}	Fossil fuel resources and other inputs in sector i ($i \in FF$) and region r
σ^{ELE}_{ir}	Electricity and the composite of other secondary energy goods in the energy aggregate of sector i and region r
σ^{FE}_{ir}	Energy goods in the non-electric energy composite of sector i and region r
σ^A_{ir}	The import composite and the domestic good variety of sector i and region r
σ^A_{ir}	Imports of good i in the import composite of region r
η_{ir}	Transformation elasticity between export supply and domestic supply of sector i and region r

Tab. 4: Notations for variables

Endowments and other parameters	
$\overline{L}_r$	Labor endowment of region r
$\overline{K}_r$	Capital endowment of region r
$\overline{Q}_{ir}$	Endowment of region r with fossil fuel resources i ($i \in FF$)
$\overline{G}$	Public good provision in region r
$\overline{I}$	Investment demand in region r
$\overline{B}$	Balance of payment deficit or surplus of region r
$\overline{CO2}_r$	CO_2 emissions constraint of region r
$a_i^{CO_2}$	CO_2 emissions coefficient for secondary energy good i ($i \in FE$)