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Abstract

Deep decarbonization requires electrification of energy-related processes across all sectors of the economy. This so-called sector coupling has important implications for quantity-based regulations in the electricity sector which overlap with measures that promote electricity-based technologies in other sectors, like subsidies for electric vehicles, CO_2 taxes on fossil technologies, or a separate ETS in the transport and buildings sectors. We show this for emissions trading systems (ETS) and renewable portfolio standards (RPS). The switch to electricity-based technologies usually strengthens an existing RPS. For the EU ETS, the switch raises demand for emission allowances in countries with such additional policies, but emission reductions come from all countries within the ETS. There is thus a reverse waterbed effect. Numerical simulations for overlapping regulations in the EU and the US underpin the policy relevance. They suggest that overlapping policies should generally target sectors not covered by quantity instruments such as an ETS or RPS.

Keywords: Sector coupling, overlapping regulation, cap and trade, renewable portfolio standards, unilateral action, reverse waterbed effect

JEL Classification: H23, D58, Q54, Q38

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1 Introduction

More than 140 countries, covering about 88% of global greenhouse gas emissions, have set a net-zero emissions target (Net Zero Tracker, 2023). To achieve this goal, fossil fuels must be replaced by energy from carbon-free renewable sources. This requires linking the energy consuming sectors with the electricity sector, which is commonly 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 outcome of climate policies which overlap with quantity-based instruments that regulate emissions from electricity generation, such as multilateral emissions trading systems (ETS) and renewable portfolio standards (RPS). Examples of overlapping policies are CO_2 taxes, subsidies for BEVs and renewable energies, as well as a separate ETS in the transport and buildings sectors. This setting reflects a second-best world where calls for uniform CO_2 pricing across all sectors have failed so far. The topic is of growing importance as sector coupling is pivotal for the transition towards a zero-emissions economy and quantity-based instruments are among the most important climate policy measures. As of 2024, 36 ETS are in place, covering about 18 per cent of global greenhouse gas emissions — compared to just 6 per cent covered by CO_2 taxes (ICAP, 2024; World Bank, 2024).[1] A related policy are renewable portfolio standards (RPS) — also called renewable electricity standards — that require a certain percentage of a utility's electricity to come from renewable energy sources.[2] Such RPS have been implemented in 35 countries, including China and the USA, where they are used in 29 states and the District of Columbia (Barbose, 2023; REN21, 2023).

The emissions trading system in the European Union (EU ETS) is the world's first and so far the largest multinational ETS.[3] Like almost all ETS, it includes power generation as the most important source of CO_2 emissions. Several countries have implemented additional regulations in this sector, such as the subsidization of renewable energies and the phasing out of coal-fired power plants. It is well known that such overlapping policies are a potential source of excess cost (see Bovenberg and Goulder (1996) for a seminal contribution). Moreover, if they are taken *within* the ETS sector, they 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. Metaphorically speaking, the reduced emissions pop up at the other side of the waterbed (see, e.g., Eichner and Pethig, 2019). Similarly, in their discussion of plans for a national renewable portfolio standard with trading, Goulder and Stavins (2011) pointed out that the imposition of stricter standards by "green" states would also lead to a waterbed effect that could approach 100 percent.

By contrast, in this paper we focus on the economic and environmental impacts of policies in

[1] An additional 22 ETS are at different stages of development and consideration (ICAP, 2024).

[2] Goulder and Stavins (2011) point out that "A renewable electricity standard with trading ... can be thought of as CO_2 cap-and-trade systems where the difference in carbon intensity among the three fossil fuels — coal, petroleum, and natural gas — is ignored and (depending upon the treatment of other fuel sources) the zero-carbon properties of hydro and nuclear are ignored."

[3] In 2023, it accounted for nearly two-third of revenues that have been raised by all ETS (ICAP, 2024, p. 26).

sectors not covered by the quantity instrument (ETS or RPS), hereafter referred to as the other energy consuming (OEC) sectors. In the EU, the sectors *outside* the ETS currently account for roughly half of CO_2 emissions, mainly stemming from fossil-fuel-based transport and heating. In our main analysis, 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 that can substitute fossil-fuel-based energy services. 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 regulated by the ETS 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 countries with unilateral action are taken from the other side of the waterbed. By contrast, emissions in the OEC sectors of the other countries increase because the higher electricity price discourages the switch to electricity-based technologies.

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.[4] Sometimes it is then recommended to focus on improving the fuel efficiency of vehicles with internal combustion engines. 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 respect, unilateral subsidies for BEVs accelerate a coal phase-out, especially when the CO_2 emissions intensity of electricity generation is high. Note that this would be very different with a price instrument rather than a quantity instrument. For example, assuming a fixed carbon price, Gillingham, Ovaere, and Weber (2024) show for the USA that policies to greatly increase the market share of BEVs would not significantly reduce CO_2 emissions because BEVs are more likely to be powered by coal.

In the first part of the paper, we develop a simple theoretical model comprising N jurisdictions. Each jurisdiction has an electricity (ELE) sector regulated by a quantity instrument and an OEC sector (transport/heating) that represents all other sectors with electrification potential. Both sectors operate with a clean (renewable-electricity-based) and a dirty (fossil-fuel-based) technology. Sector coupling and the quantity instrument create linkages between sectors and jurisdictions, respectively.

In the case of an ETS, if a country (or a group of countries) unilaterally taxes the dirty technology or subsidizes the clean technology in the OEC sector, output shifts towards the clean technology. The resulting higher electricity demand increases the emissions allowance price in the ELE sector and thus the costs of the dirty technology in *all* countries covered by the ETS. For the country acting

[4] 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, Hung, Völler, Agez, Majeau-Bettez, and Strømman (2021, p. 8) write in their analysis of the climate footprint of BEVs: "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."

unilaterally, we show that emissions fall in the OEC sector but rise in the ELE 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, albeit a separate one. This reflects that in 2023 the EU established a new, separate emissions trading system named ETS2 that covers emissions from fuel combustion in buildings, road transport and additional segments of the OEC sector (Directive (EU) 2023/959).[5] Obviously, the unilateral tax and subsidy instruments would no longer be effective due to the waterbed effect in the OEC sector. Therefore, we examine the unilateral cancellation of ETS2 emission allowances. This policy also induces sector coupling with feedback effects on the ETS for the power sector, similar to the unilateral tax or subsidy in the preceding analysis. However, the direct effects of allowance cancellations in the OEC sector (i.e., ETS2) are more symmetrically distributed between countries as they all face the same higher allowance price. Moreover, we compare this with the alternative of cancelling allowances in the ELE sector (i.e., ETS). This 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 ETS2 allowances are more in line with the envisaged energy transition as they also raise the output of the clean, renewables-based technology in ELE sector.

Renewable portfolio standards (RPS) share similar effects of overlapping regulations. Motivated by the Inflation Reduction Act (IRA), we show that subsidies for renewable energies in the electricity sector weaken the RPS by reducing the price of renewable electricity credits (RECs), which are used by utilities to meet mandated renewable energy quotas. By contrast, subsidies for electricity-based technologies such as electric vehicles and heat pumps, i.e., in sectors not covered by the RPS, tend to strengthen the RPS.

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 both applications, the ETS in the EU and the RPS in the US, we find that all qualitative results from the theoretical analysis still hold in a 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 EU ETS, unilateral taxes make the other countries also bear some of the economic adjustment costs of emission reductions. This is not the case if there is an ETS2 and emission allowances are cancelled unilaterally. Moreover, the scenario with a second ETS allows us to compare the symmetric policies of unilateral allowance cancellations in either the ETS for the ELE sector or the ETS2 for the OEC sectors. It turns out that the latter involve substantially lower economic adjustment costs for achieving EU-wide emissions reduction targets, as reductions are more evenly distributed across both sectors. Finally, for the RPS in the US we find that subsidies in the OEC sectors lead to substantially higher overall emission reductions than the same subsidy rate in the electricity sector would achieve. In conclusion, our analysis shows that accounting for sector coupling leads to strong arguments for targeting overlapping policies to the OEC sectors (transport/heating),

[5] The ETS2 is expected to be fully operational in 2027, with a cap set to bring emissions down by 42% below 2005 levels by 2030. Additional allowances may released if their price exceeds € 45, which is well below the price of EU ETS emission allowances in recent years, demonstrating the need to treat the two systems as separate.

rather than to the ELE 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, 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. Burtraw, Holt, Palmer, and Shobe (2022) have pointed out that price-responsive supply schemes for emission allowances that respond to lower ETS prices by tightening the cap would help to resolve the waterbed effect. Indeed, some emissions trading systems have implemented price floors and ceilings or related measures like the cost containment reserve in the RGGI so that there no longer is a strict cap (ibid.). Similarly, in response to very low allowances prices, the EU ETS enacted a Market Stability Reserve (MSR) that removes allowances from the auction, some of which are cancelled (Borghesi, Pahle, Perino, Quemin, and Willner, 2023). We ignore such steps towards hybrid price-quantity instruments. It is also expected that the MSR for the EU ETS will no longer be effective in 2030, the year we focus on in our numerical simulations.

The literature has stressed the need to 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 energy efficiency 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 much more detailed CGE model.

Regarding renewable portfolio standards, most of the literature has focused on the situation in the US and the effects of strengthening the RPS (e.g., Fullerton and Ta, 2024). Hollingsworth and Rudik (2019) show that regulations that overlap with RPS induce emission reductions in other states through trading of renewable electricity credits used for RPS compliance. More closely related to our analysis, Fischer, Greaker, and Rosendahl (2018) have noted that subsidizing renewable energy technology equipment will make a renewable portfolio standard easier to meet. Yan, Sun, and Guo (2022) examine the joint use of a cap-and-trade mechanism and renewable portfolio standards in China.

The remainder of the paper starts with the theoretical analysis: Subsection 2.1 lays out the analytical model; Subsections 2.2 and 2.3, which are motivated by the EU ETS, analyse unilateral CO_2 taxes and subsidies in the OEC sectors, as well as the cancellation of allowances; Subsection 2.4 examines the effects of green subsidies overlapping with an RPS, as is the case in the US. Section 3 provides the numerical analysis: Subsection 3.1 features a non-technical summary of the CGE model and describes the empirical data used for model calibration; Subsections 3.2 examines overlapping regulation in EU climate policy design; Subsection 3.3 presents illustrative simulations for the US on how green subsidies interact with an RPS. Finally, Section 4 concludes and Appendices A and B contain the proofs and an algebraic description of the CGE model.

2 Theoretical analysis of sector coupling effects

2.1 Analytical model

Consider a set of $N = \{1, ..., n\}, n \geq 2$ jurisdictions that are indexed i. As the EU ETS is our main example, we refer to them as "countries". However, the analysis also applies to national emissions trading systems (ETS) where 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. Likewise, in our analysis of renewable portfolio standards (Section 2.4), i represents a single state or province.

We split the economy of each country into an ELE sector that comprises electricity generation and an OEC sector that covers all other energy consuming activities with the potential for "electrification" (sector coupling). Thus, the only output of the ELE sector is electricity (denoted y), whereas the most relevant outputs of the OEC sector are transportation services and heating/cooling of buildings (denoted x). For concreteness, we sometimes refer to the ELE and OEC sectors as the electricity and transport/heating sectors, 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

ELE sector and on the replacement of fossil fuels by electricity in the OEC sector.[6]

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 ELE and OEC sectors (superscripts y and x) by $C_{ci}^y(y_{ci}), C_{di}^y(y_{di})$, and $C_{di}^x(x_{di})$.[7]

The "clean" technologies in the OEC sector like electric vehicles and heat pumps 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 with the clean OEC technology 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 OEC services like transport and heating.

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} will 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 with the cost functions, we drop

[6] 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.

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

Tab. 1: Interpretation of parameters for different policy settings

	ψ_i	$\psi_i y_{di}$	λ_i	$\lambda_i y_{ci}$	κ_i	$\kappa_i x_{di}$
ETS in ELE sector	$\nu\alpha_y$	νe_{yi} costs of ETS allowances in ELE sector	0	0	$\tau_i\alpha_x$	$\tau_i e_{xi}$ costs of tax in OEC sector
ETS in ELE and in OEC sector	$\nu\alpha_y$	νe_{yi} costs of ETS allowances in ELE sector	0	0	$\varphi\alpha_x$	φe_{xi} costs of ETS2 allowances in OEC sector
RPS in ELE sector	$\frac{r_i}{1-r_i}\gamma_i$	$\frac{r_i}{1-r_i}\gamma_i y_{di}$ costs of RPS for dirty producers	$\gamma_i + s_i$	$(\gamma_i + s_i)y_{ci}$ revenues from RPS and subsidy for clean producers	0	0

superscripts x, y for parsimony and assume that $u_i(x_i)$ and $u_i(y_i)$ are increasing and strictly concave.

We analyze the effects of policies that overlap with an already existing quantity-based regulation in the electricity sector for three different settings:

1. a tax, τ_i, on emissions from the dirty technology, or a subsidy, σ_i, for the clean technology in the OEC sector, if there exists an ETS with allowance price ν in the ELE sector (Section 2.2);

2. the cancellation of allowances in the OEC sector if that sector has an additional "ETS2" with allowance price φ (Section 2.3);

3. subsidies, σ_i, for the clean technology in the OEC sectors and subsidies, s_i, for electricity from renewable energies if the ELE sector has a renewable portfolio standard, $r_i := \frac{y_{ci}}{y_{ci}+y_{di}}$, and each unit of renewable generation yields one renewable electricity credits (REC), which fossil producers purchase at price γ_i to fulfil the RPS (Section 2.4).

For all policies the (concave) profit functions for the respective firms can be stated as (π^y_{di} are profits of the representative firm in the dirty electricity sector of country i, and so on):

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

The first term on the right hand sides are revenues and the second term are production costs, which in the case of clean transport/heating also include the costs of electricity inputs, $p_{yi}\beta x_{ci}$. The last terms represent the costs and revenues that follow from the different policies. Specifically, σ_i is the subsidy for the clean technology in the OEC sector, whereas the specification of the other terms varies for the three different policy settings as summarized in Table 1.

Profit maximization yields the following first-order conditions for all $i \in N$:

$$p_{yi} = C'_{di}(y_{di}) + \psi_i, \tag{5}$$

$$
\begin{aligned}
p_{yi} &= C'_{ci}(y_{ci}) - \lambda_i, & (6)\\
p_{xi} &= C'_{di}(x_{di}) + \kappa_i, & (7)\\
p_{xi} &= C'_{ci}(x_{ci}) + p_{yi}\beta - \sigma_i. & (8)
\end{aligned}
$$

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 binds. Solving it for z and substitution into the concave utility function yields the first-order conditions that marginal utility equals prices for $i \in N$:

$$
\begin{aligned}
u'_i(y_i) &= p_{yi}, & (9)\\
u'_i(x_i) &= p_{xi}. & (10)
\end{aligned}
$$

Finally, prices follow from the respective market clearance conditions that demand equals supply. These are for the OEC sector

$$x_i^D(p_{xi}) = x_{di}^S(p_{xi}) + x_{ci}^S(p_{xi}),\ i \in N, \tag{11}$$

and for the ELE sector

$$y_i^D(p_{yi}) = y_{di}^S(p_{yi}) + y_{ci}^S(p_{yi}) - \beta x_{ci},\ i \in N, \tag{12}$$

where $\beta x_{ci} = y_{xi}$ is electricity input into the clean technologies of the OEC sector.

2.2 Unilateral climate policies with an ETS only for the ELE sector

In this and the next subsection, the ELE sector is regulated by an ETS with auctioned allowances, an exogenous emissions cap $\bar{e}_y$, and an endogenous allowance price ν that follows from the market clearance condition for the allowance market,[8]

$$\sum_{i \in N} \alpha_y y_{di}(\nu) = \bar{e}_y. \tag{13}$$

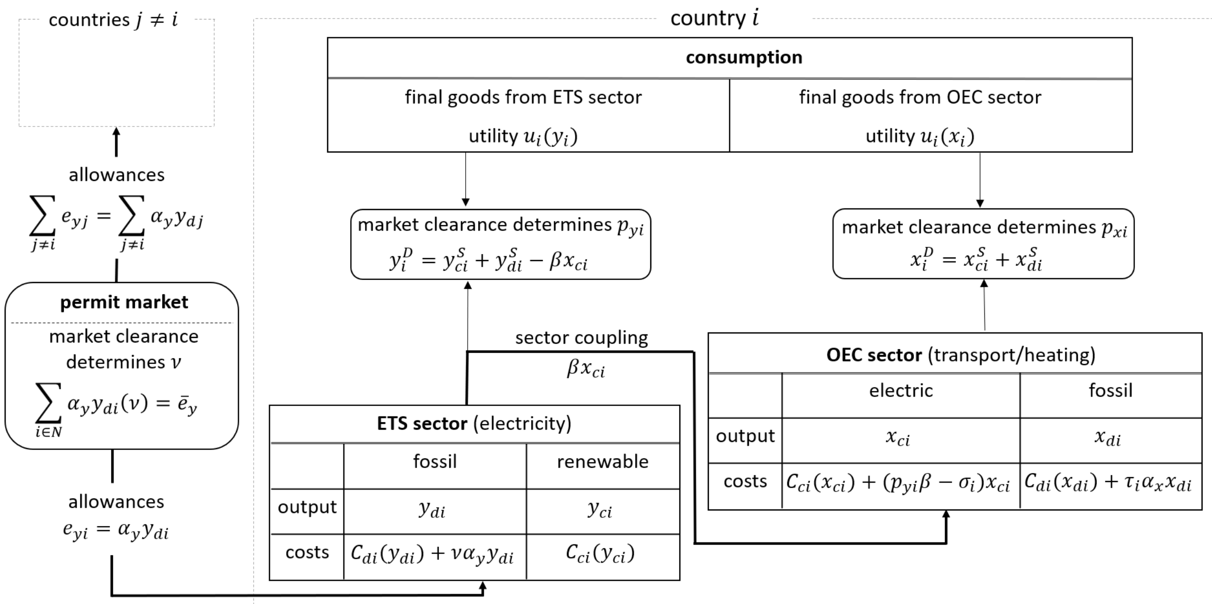
For the OEC sector, we first consider the case that it is not regulated by an ETS. A unilateral policy in this sector then takes the form of a unilateral increase of either the tax, τ_A, per unit of emissions from the dirty technology, or of the subsidy, σ_A, per unit of output from the clean technology, where A denotes the country that implements the unilateral policy (i.e., $d\tau_j, d\sigma_j = 0$ for all other countries $j \in N \backslash A$).

Figure 1 graphically illustrates this setting. In each country i, households consume the output of the ELE 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 ELE sector as an input. This "linkage between sectors" is represented by the bold vector labelled "sector coupling". Moreover,

[8] Thus, Eqs. (5) to (12) and (13) yield a system of $8n + 1$ equations that determines the $4n$ output values, $2n$ consumption values, and $2n + 1$ prices.

the ELE sector requires emission 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 of a unilateral policy in the OEC sector — an emissions tax τ_i or a renewables subsidy σ_i — 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 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 ELE 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 pattern 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 ELE 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 the dirty technology in the OEC sector and a subsidy on the clean one both induce a shift from the dirty to the clean technology, hence $dx_{dA} < 0$ and $dx_{cA} > 0$. As the clean technologies like BEVs and heat pumps are electricity-based, production from dirty and clean electricity sources rises, $dy_{dA}, dy_{cA} > 0$. To induce firms in country A to produce more electricity, the electricity price must rise ($dp_{yA} > 0$). This raises production cost of the electricity-based clean OEC technology. Together with the tax on the dirty technology, the output price in the OEC sector 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 the electricity-based clean OEC technology in the other countries more costly. Hence its output falls ($dx_{cj} < 0$) and its price rises ($dp_{xj} > 0$), which raises the profitability of the dirty OEC technology ($dx_{dj} > 0$). The main difference between the two instruments is that the tax penalizes dirty technologies, whereas the subsidy promotes clean technologies. Therefore, overall output of the OEC sector 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 rise, 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 ELE 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 in that sector, 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 ELE 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 like mobility of capital and labor across sectors would lead to additional effects. 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 with separate ETS for the ELE and OEC sectors

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, albeit a separate one, called ETS2. In this case, the policies that we have analysed so far — taxes for the dirty technology and subsidies for the 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 ETS2 opens up the new policy option to cancel ζ emission allowances in the OEC sector. Accounting for this option, the market clearance condition for the ETS2 allowance market is:

$$\sum_{i \in N} \alpha_x x_{di}(\varphi) = \bar{e}_x - \zeta, \qquad (14)$$

where $\bar{e}_x$ is the exogenous emissions cap.[9] Intuitively, the cancellation of allowances drives up the allowance price in the OEC sector ($d\varphi > 0$), making its dirty technology more expensive. 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 increases 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

[9] The solution now follows from Eqs. (5) to (12), Eq. (13), and Eq. (14) for the parameter values in Table 1 and $\sigma_i = 0$ (we do not analyse a subsidy for the clean technology in this subsection).

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 ETS2) 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 ETS2 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 ELE 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 ETS2 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 ELE 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 ($\sum_{i \in N}(dy_{di} + dy_{ci}) < 0$).

2.4 Renewable portfolio standards and subsidies in the electricity and OEC sectors

So far the analysis was motivated by the EU ETS and focused on the implementation of additional emission reduction policies by a subset of regions. However, the implications of sector coupling for systems of overlapping regulation are not restricted to such a setting. We now show this for a regulatory framework motivated by two policies that dominate the climate policy space in the US. The Inflation Reduction Act (IRA) of 2022 is the most important federal climate policy. It includes \$500 billion in new spending and tax breaks, with clean electricity and transmission taking the largest share, followed by clean transport, including incentives for BEVs (Jenkins, Mayfield, Farbes, Jones, Patankar, Xu, and Schivley, 2022). This overlaps with existing renewable portfolio standards (RPS) that are adopted in 29 states (plus the District of Columbia). Generally, an RPS is combined with a renewable electricity credit (REC) trading system that enables power suppliers to achieve the RPS requirement in a cost-effective way. This makes it related to a cap-and-trade system.

We denote the RPS in state i by $r_i := \frac{y_{ci}}{y_{ci}+y_{di}} \in (0,1)$, i.e., by the share of renewables, y_{ci}, in total electricity production, $y_{ci}+y_{di}$. Each unit of renewable generation yields one REC, which are purchased by fossil producers to fulfil the RPS. The REC price, denoted γ_i, clears the market. Accordingly, we ignore trading of RECs across state borders for parsimony (see Hollingsworth and Rudik (2019) on interstate trading). This implies revenues $\gamma_i y_{ci}$ for renewable producers and payments $\gamma_i \frac{r_i}{1-r_i} y_{di}$ for fossil producers as stated in Table 1.[10]

The RPS overlaps with policies under the IRA that we model as subsidies, σ_i, per unit of output from the clean technology in the OEC sectors (transport/heating) as well as subsidies, s_i, per unit of electricity from renewable energies.

From the first-order conditions (5) and (6) in the electricity sector, it follows that $C'_{ci}(y_{ci}) - C'_{di}(y_{di}) = \left(\frac{1}{1-r_i}\right)\gamma_i + s_i$. We restrict the analysis to situations with a binding RPS, which implies a positive price of RECs. Therefore, marginal production cost of renewable producers exceed those of fossil producers. We take this difference and, thus, the REC price, γ_i, as indicating the "strength" (or "restrictiveness") of the RPS. Accordingly, a higher level of electricity from renewable energies makes the RPS more restrictive if

$$\frac{d}{dy_{ci}}\left[C'_{ci}(y_{ci}) - C'_{di}(y_{di})\right] \quad = \quad C''_{ci}(y_{ci}) - C''_{di}(y_{di})\frac{1-r_i}{r_i} > 0, \tag{15}$$

where we have used $y_{di} = \frac{1-r_i}{r_i} y_{ci}$, which follows from the definition of the RPS, to calculate the derivative of $C'_{di}(y_{di})$. Observe that this is more likely to be the case if the RPS is more strict because $\frac{1-r_i}{r_i}$ is decreasing in r_i. Condition (15) requires that the marginal costs of electricity production from fossils do not increase much more rapidly than those of electricity production from renewables. Otherwise, fossil producers would not want to keep up with a higher output of electricity from renewables — unless the REC price falls — because producing electricity from fossils simply becomes too expensive. The following result states the main effects of subsidies that overlap with an RPS.

Proposition 5. *Suppose that a region i has a renewable portfolio standard.*

a) Subsidies for renewable energies in the electricity sector weaken the overlapping RPS, i.e., $ds_i > 0$ leads to $d\gamma_i < 0$ (and $dp_x < 0, dp_y < 0$). By contrast, subsidies for the clean technology in the OEC sector (transport/heating) strengthen the overlapping RPS iff a higher level of electricity from renewable energies makes the RPS more restrictive, i.e., iff (15) holds, $d\sigma_i > 0$ leads to

[10] See, e.g., Fischer (2010) for a similar specification and note that a binding RPS implies that this system is revenue neutral, i.e., $\gamma_i y_{ci} = \gamma_i \frac{r_i}{1-r_i} y_{di}$.

$d\gamma_i > 0$ (and $dp_y > 0, dp_x < 0$).

b) Both policies do not only increase the electricity output from renewable energies, but also that of fossil producers and related emissions ($dy_{ci}, dy_{di} > 0$). By contrast, output and emissions from the dirty technology in the OEC sectors fall ($dx_{di} < 0$), whereas output from the clean technology rises ($dx_{ci} > 0$).

As mentioned in the introduction, already Fischer et al. (2018) pointed out that subsidizing renewable energy technologies ($ds_i > 0$) raises not only their output ($dy_{ci} > 0$), but also output and emissions from fossil producers ($dy_{di} > 0$) because the higher supply of RECs makes the RPS easier to meet ($d\gamma_i < 0$). However, sector coupling leads to a reverse effect on emissions in the OEC sectors as the electricity-based clean technologies like BEVs and heat pumps benefit from the lower electricity price ($dp_y < 0, dx_{ci} > 0$). This makes output of the OEC sector cheaper ($dp_x < 0$) so that production of its dirty, fossil-fuel based technologies becomes less profitable ($dx_{di} < 0$) and its emissions fall.

Subsidies for the clean OEC technologies ($d\sigma_i > 0$) directly lower their costs. Hence output rises ($dx_{ci} > 0$) and the price falls ($dp_x < 0$) so that output of the dirty OEC technology and emissions fall again ($dx_{di} < 0$). Here too, sector coupling results in a reverse effect on emissions in the other sector because the higher electricity demand comes from the clean and the dirty technology ($dy_{ci}, dy_{di} > 0$) due to the binding RPS.

3 Numerical analysis of sector coupling effects

The economic responses to climate policy regulations are determined by a variety of substitution, output, and income effects, which are more complex than presented in the analytical model. Therefore, we complement our theoretical analysis with computable general equilibrium (CGE) simulations based on empirical data. The CGE analysis not only allows a robustness check of the qualitative results of the theoretical analysis, but also provides quantitative estimates of economic impacts.

We first address specific model features and lay out the data sources for model parameterization. Our simulation analysis then focuses on overlapping unilateral climate policy regulations across EU Member States with a pre-existing EU-wide emissions trading system (EU ETS) that sets a quantitative emissions budget for the power sector and other emissions-intensive industries. In addition, we provide some illustrative analysis of how green subsidies under the US Inflation Reduction Act interact with pre-existing renewable portfolio standards (RPS) as a cornerstone of US climate policy.

3.1 Model and data

Our numerical model adopts the standard top-down CGE structure for representing price-responsive production, consumption, and trade activities (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 labor, fuel, and materials with technology-specific resources (capital embodied in power plants and natural resources such as water, sun, wind, biomass). For each technology, power generation takes place with decreasing returns to scale and responds to changes in electricity prices according to technology-specific supply elasticities. 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). Practical examples of such power-to-X technologies 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.

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 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 trade, as well as information on physical energy flows and CO_2 emissions for 40 regions and 31 sectors. The electricity sector in the JRC dataset is disaggregated by region into 8 discrete generation technologies and a composite sector for power transmission and distribution.

Besides the explicit information on individual power generation technologies, another appealing feature of the JRC dataset is that it contains baseline projections of future economic activities and energy use in five-year intervals up to 2050. For our numerical simulations, we take the forecasted input-output tables in 2030 as the baseline scenario, against which we measure the impacts of additional overlapping climate policy regulations.

The JRC dataset can be flexibly aggregated across sectors and regions to reflect specific requirements of the policy issue under investigation. Table 2 provides an overview of the sectors (incl. power generation technologies) in the composite dataset for the numerical analysis. The aggregation of regions depends on the geographical coverage of different climate policy regulations as laid out in Sections 3.2 and 3.3 below.

Tab. 2: Sectors in the composite dataset

Energy sectors	**Non-energy sectors**
Primary energy sectors	*Emissions-intensive sectors*
Crude oil, natural gas, coal	Composite of chemical products, non-metallic minerals, iron and steel, non-ferrous metals, paper products and publishing, air transport
Secondary energy sectors	
Refined oil products	
Electricity transmission and distribution	
Electricity generation technologies	*Rest of industry and services*
fossil-fuel based: coal, oil, natural gas	Composite of all other remaining industrial and service sectors in the JRC dataset
renewable energy based: hydro, wind, solar, biomass	
nuclear	*Final consumption*
	Household and government demands

We retain all the different primary and secondary energy carriers of the original dataset: coal, crude oil, natural gas, refined oil, and electricity. This breakdown is essential to distinguish energy goods by CO_2 intensity and the degree of energy substitutability. Given the pivotal role of electricity for decarbonization, we treat all power generation technologies of the JRC dataset as explicit production sectors. As to non-energy sectors, we include a composite of emissions-intensive and trade-exposed (EITE) industries (i.e., chemical products, non-metallic minerals, iron and steel, non-ferrous metals, paper products and publishing, and air transport) that are potentially most sensitive to emissions regulations. The rest of other industries and services are aggregated to a single composite sector.

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. As for supply elasticities for power-to-X technologies, we are not aware of any empirical studies to date. This reflects that such technologies only just start being operated at a larger scale because they are often not yet profitable without subsidies. The market penetration is then determined by estimates on the initial cost gap for the break-even point and technological capacity bounds for the replacement of fossil-fuel based energy services by electricity-based energy services.

3.2 Overlapping regulation in EU climate policy design

The EU's main climate policy instrument so far is an emissions trading system (EU ETS). In addition to power generation — the ELE sector of the analytical model — it also covers emissions-intensive industries; hence we refer to this as the ETS sector. Countries' shares of allocated emission allowances are oriented at their emissions in 2005.[11] All other energy consuming (OEC) sectors are subject to the

[11] 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

EU effort sharing regulation (ESR), which sets country-specific emissions reduction targets for 2030 compared to 2005 levels (Regulation (EU) 2018/842, Annex I).

In the JRC dataset, we sort EU countries according to the stringency of emissions reduction targets under the ESR. The left column in Table 3 compromises countries with targets above 25%. It consists of the most ambitious group with targets above 35% — of which we treat the large countries Germany, France, and the United Kingdom[12] separately — followed by a regional aggregate of countries with moderate (25-35%) targets. The right column in Table 3 comprises countries with targets below 25%. It consists of Poland — a politically influential large CO_2 emitter whose electricity generation is predominantly based on coal —, the other Eastern European countries (EEC) and a residual of smaller Southern European countries, denoted Rest of Europe (RoE). For the sake of compactness, we limit the explicit representation of the remainder of the global economy to a single composite region, denoted Rest of the World.

Tab. 3: Regions in EU ETS analysis

Members of climate coalition (COA)	**Non-members (NCOA)**
High targets >35%	*Low targets <25%*
Germany, United Kingdom, France.	Poland
Composite of Austria, Denmark, Finland, Netherlands, Luxembourg, Sweden	Composite of *Eastern European Countries (EEC)*: Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Romania, Slovakia, Slovenia
Moderate targets 25%–35%	
Composite of Belgium, Italy, Ireland, Spain	*Rest of Europe:* Greece, Malta, Portugal, Cyprus
Rest of World: All other countries and regions in JRC dataset	

Our simulation analysis of EU climate policies focuses on 2030 as a milestone year. Under the Paris Agreement in 2015 the EU pledged a 40% greenhouse gas emissions reduction by 2030 from 1990 emission levels. 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, the most important parts of which were adopted by the European Council in April 2023, 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.* This policy raises the ETS allowance price from 39 $/t$CO_2$, which the JRC dataset reports for 2030, to 96.9 $/t$CO_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 argue that ESR reduction targets below 25% reflect lower ambitions and assume that countries in this

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 are therefore not available for 2030.

[12] 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.

group (called "NCOA", see Table 2) are unwilling to increase their emission reductions beyond those in the *ref* scenario. By contrast, we associate countries with ESR reduction targets above 25% with higher environmental concerns and assume that they are willing to *unilaterally* fill the gap such that *overall* EU emissions meet the Fit-55 target. We call this group the climate coalition "COA".

We examine three different scenarios to achieve this, which closely follow our theoretical analysis. They are summarized in Table 4 and 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*,[13] 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%.[14] The second scenario, called *kill-OEC,* reflects that in 2023 the EU created a second emissions trading regime (the so-called ETS2) for emissions in the OEC sectors of all EU member states. In this scenario, an ETS2 is already in place before the implementation of the unilateral emissions reduction policy, and we assume that the initial endowment with ETS2 allowances corresponds to countries' emissions in scenario *ref.* The unilateral policy is then for coalition countries to cancel (or "kill") enough ETS2 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.[15] In addition, cooperative reductions of all EU countries in the OEC sectors now fill the gap to achieve the Fit-55 target.[16]

Effects on emissions and electricity markets in EU

For the three EU climate policy scenarios, Table 5 compares the signs of the comparative statics from our analytical model in Propositions 1 to 4, with the corresponding quantitative results from the numerical CGE simulation. 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 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 5 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

[13] 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.

[14] Initial emissions prices for OEC sectors are zero in the JRC dataset reports for 2030. 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.

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

[16] Cooperative action is implemented as a uniform downscaling of ETS2 allowances across all EU countries.

Tab. 4: 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.

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 ETS2. This reflects that the unilateral tax in scenario *tax-OEC* incentivices only emission reductions in the OEC sectors of COA countries (by 32.9%), whereas OEC emissions in NCOA even increase (by 0.8%). By contrast, *kill-OEC* provides the same CO_2 price signal to all countries so that emission reductions in OEC sectors are distributed more evenly across all EU countries.

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*). Breaking this down to the three individual NCOA regions in our CGE model, emission reductions in *tax-OEC* are −9.1% for Poland, −5.8% for EEC and −3.4% for RoE. This correlates positively with the emissions intensities

Tab. 5: 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	$dy_{cA} > 0$	$dy_{cA} > 0$	$dy_{cA} > 0$	5.4	4.4	13	118.7 TWh	96.6 TWh	286 TWh
COA	fos + ren	+	?	?	7.7	5.9	−4.5	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	$dy_{cj} > 0$	$dy_{cj} > 0$	$dy_{cj} > 0$	3.6	6.2	32.6	14.1 TWh	24.1 TWh	127 TWh
NCOA	fos + ren	–	?	?	−1.6	2.5	−18.3	−10.4 TWh	16.1 TWh	−119 TWh
total electricity gen.	fos + ren	+	+	–	5.8	5.2	−7.2	191 TWh	171 TWh	−236 TWh

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

of electricity generation in these regions, which are (in gCO_2 per kwh) 355, 117, and 61 respectively. Therefore, policies that favor green technologies in the OEC sector are particularly detrimental for the dirtiest power generators. Especially 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 ETS2 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,[17] which makes sector-coupling technologies more expensive. As a result, electricity demand falls so that electricity generation from fossils and renewables decreases significantly for both COA and NCOA (by −7.2% 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 electricity generation from fossils and renewables for COA and NCOA (+5.8 under *tax-OEC* and +5.2% under *kill-OEC*).

Welfare effects in EU

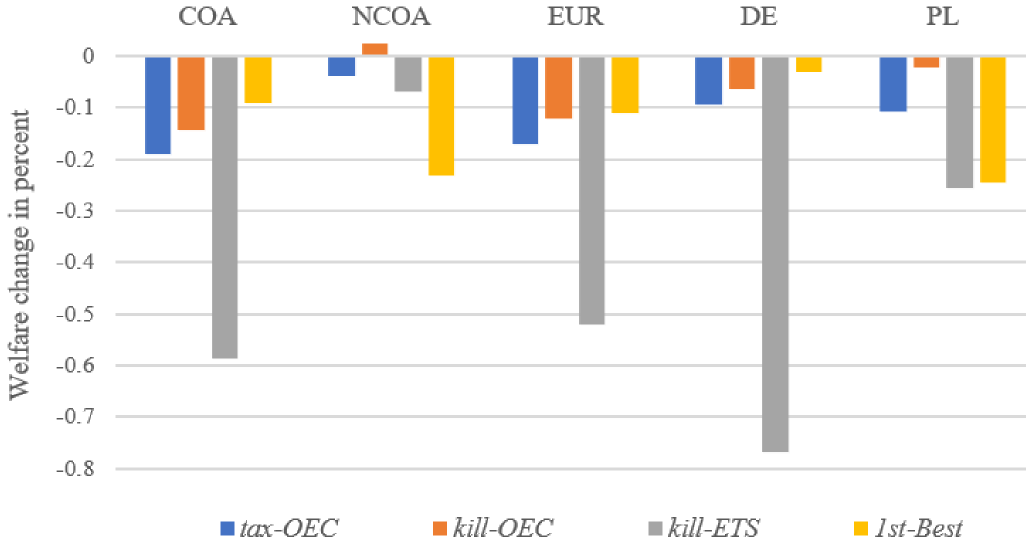
In addition to quantifying the results derived from the theoretical partial equilibrium analysis, the numerical CGE analysis provides estimates of the economy-wide adjustment costs of alternative EU climate policy designs. We report these costs in terms of a standard welfare metric, the Hicksian equivalent variation (HEV) in income. As the various scenarios achieve an identical level of EU-wide emission reductions, we obtain a coherent cost-effectiveness comparison.

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 in *kill-ETS* both cooperative and unilateral allowance reductions take only place in the ETS

[17] These prices are country-specific and in Table 5 we have reported them for Germany and EEC.

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



sector, whereas in *tax-OEC* and *kill-OEC* emission reductions are distributed across both sectors. 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 *tax-OEC*. 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 5). 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 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 5). 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.

Sensitivity analysis

In the description of our sensitivity analysis, we focus on parameters related to sector coupling where empirical data are lacking: (*i*) the supply elasticities that capture the ease of expansion by renewable power generation, (*ii*) the initial cost gaps of clean technologies in the OEC sector towards breaking even, and (*iii*) the upper bound on the expansion of these clean technologies ((ii) and (iii) capture the ease of substituting dirty technologies in the OEC sector via clean technologies). For each of these dimensions we consider different sets of parametric assumptions.

In the central case formulation (underlying our results in Table 5 and Figure 2), supply elasticities of renewable energy technologies are assumed to be twice as high as those of fossil fuel based power technologies (with supply elasticities of 2 versus 1) — while for energy policy reasons and resource availability constraints we limit supply from nuclear power and hydro power at the benchmark level. In the sensitivity analysis, we double and halve the supply elasticities of renewable power technologies. The cost cap for clean technologies in the central case simulation is assumed at 25% of the break-even price; this cost cap is reduced to 0% or increased to 50% in our piecemeal sensitivity analysis. For the capacity constraint, we assume in the core parameterization a 50% market potential of clean technologies to substitute for dirty technologies, which in the sensitivity analysis is either decreased to 25% or increased to a 100%.

When the scope for sector coupling becomes more restricted because of higher cost and more limited capacity, effective emissions reductions in the OEC sector require higher CO_2 prices. This shows up most prominently in scenario *tax-OEC* with its relatively large emission reduction requirement through unilateral emissions pricing of OEC emissions in the coalition countries, and to a lesser extent in scenario *kill-OEC* where increased CO_2 prices in the OEC sector apply to all EU countries. The ease of sector-coupling has only limited effects on EU-wide pricing of OEC emissions in *kill-ETS* as the key channel of additional emission reductions to achieve the Fit-55 target operates in this scenario through higher allowance prices in the ETS sector.

Cheaper expansion of renewable power generation has a downward pressure on the emissions prices in the ETS sector as well as in the OEC sector across all three climate scenarios. All the findings on policy-induced shifts in power generation and emissions in the ETS and OEC sectors across coalition and non-coalition countries are robust to parametric changes in both the ease of sector coupling as well as the ease of renewable power expansion. At the macroeconomic level, the common effect of more optimistic assumptions on the cost of renewable power expansion and sector coupling is a decrease in the economy-wide cost of achieving the EU-wide Fit-55 targets for the three alternative climate policy designs.

All our key insights of the central case simulations remain robust with respect to these changes in parameter values. More specifically, for all variations in the parameter values discussed above, in scenario *tax-OEC* the reverse waterbed effect on emissions in the ETS sector of NCOA varies from -4.9% to -8.4%, and the rebound effect on emissions in the OEC sector of NCOA varies from 0.6% to 1.2%, compared to values of -6.9% and 0.8% in the main scenario reported in Table 5. As for the drivers of these effects, the emissions price in the ETS sector and the electricity price increase if supply elasticities of renewables are low and if it becomes cheaper to substitute the dirty with clean technologies in the OEC sector because this increases electricity demand in COA. As a result, both the reverse waterbed effect in the ETS sector and the rebound effect in the OEC sector increase.

3.3 Overlapping regulation in US climate policy design

We now revisit the theoretical analysis in Section 2.4, where we examined the interactions between subsidies for clean technologies and renewable portfolio standards (RPS). This resembles the setting in the US under the Inflation Reduction Act (IRA) where subsidies (or likewise tax credits) for renewable energy generation and electrification of fossil-fuel-based energy services in intermediate and final

Tab. 6: RPS — results from analytical and numerical model (in % change to *ref*)

change of ...		REC price	electricity price	emissions in sector ELE	OEC	ROE	total	electricity generation fossils	renewables
analytical model	*sub-ELE*	$d\gamma_i < 0$	$dp_y < 0$	$de_{yi} > 0$	$de_{xi} < 0$		?	$dy_{di} > 0$	$dy_{ci} > 0$
	sub-OEC	?	$dp_y > 0$	$de_{yi} > 0$	$de_{xi} < 0$		?	$dy_{di} > 0$	$dy_{ci} > 0$
numerical model	*sub-ELE*	−6.4	−0.1	5.9	−3.4	−0.6	−0.2	4.2	3.8
	sub-OEC	163.5	19.3	14.5	−11.3	−2.7	−2.4	12	9

demands overlap with state-level RPS. To obtain quantitative estimates for the interaction effects we again use our CGE model, now parameterized to JRC data for the US in 2030. The US economy is divided into the electricity (ELE) sector, which is subject to the RPS regulations, and several OEC sectors covering oil refineries and all other non-energy sectors (including final consumption) in the dataset (the residual primary energy sectors are referred as ROE below). The dataset does not break down the US economy into individual states so that complex state-specific details of RPS regulations can not be captured. Instead, we assume a US-wide uniform RPS for our simulations, which makes them more illustrative than the preceding analysis of the EU ETS.

In its baseline projections (without IRA) for 2030, the most recent Annual Energy Outlook of the US Energy Information Administration (EIA, 2023) reports a renewable share in US power generation of roughly 33%, which is 5% above that share in the JRC dataset. To reflect this, we create a reference scenario ref where the renewable share is 5 percentage points higher than in the JRC dataset. This defines the RPS and the impacts of subsidies are quantified against this ref scenario. In our central case simulations, we adopt a subsidy rate of 20%, which is paid either to producers of renewable power in the ELE sector (scenario *sub-ELE*) or to users of clean energy services (sector-coupling) in the OEC sectors (scenario *sub-OEC*). Table 6 summarizes how the qualitative predictions from the theoretical analysis translate into quantitative impacts of the numerical analysis.

The numerical general equilibrium results confirm all qualitative findings from the analytical model, suggesting that it captures the key drivers of economic responses. Furthermore, the signs for unambiguous theoretical results such as the change in economy-wide CO_2 emissions — made up of opposing effects in the OEC and ELE sectors —- are resolved based on the model parameterization. We find that both subsidization policies (*sub-ELE* and *sub-OEC*) increase not only renewable but also fossil-based power generation, due to their overlap with a binding RPS. Emissions in the electricity sector therefore increase, whereas emissions in the OEC sectors decline because fossil-fuel based energy services are substituted by subsidized electricity-based energy services. Nevertheless, the latter effect outweighs the former in both policy scenarios and total emissions decrease, with this effect being greater in the case of subsidies in the OEC sector that promote sector coupling technologies.

Regarding the stringency of the RPS (measured as a change in the REC price), it clearly decreases in the case of subsidies to renewable power generation technologies (*sub-ELE*) as this policy makes it easier to achieve a given RPS. In contrast, it is less clear how subsidies in scenario *sub-OEC* affect the REC price. By promoting electricity-based technologies like BEVs and heat pumps, such subsidies raise electricity demand. In the theory section we have argued that this leads to a higher REC price only if the evolution of marginal production costs is not too unfavorable (measured by the second derivative of the cost function) for fossils, as otherwise the share of fossils in electricity generation would fall for a given REC price. Similarly, in our numerical simulations the subsidies in scenario *sub-OEC* only increase the REC price if the supply elasticities of fossil-fuel based electricity generation exceed those of renewable electricity generation. In this case, the supply change of fossil electricity generation dominates that of renewables and the REC price has to increases to meet the RPS. For our central case simulations this is the case and the REC price more than doubles in scenario *sub-OEC*.[18] Finally, electricity prices decrease with the direct subsidies to renewable power supply (*sub-ELE*) while they increase with demand-side subsidies to electricity-based sector coupling technologies (*sub-OEC*) — note that the latter become profitable despite higher electricity prices as long as the ad-valorem subsidies paid on the purchase price of clean energy renders them cheaper than the initial fossil-fuel based energy services.

The quantitative results are sensitive to assumptions on the subsidy rate, supply elasticities for power generation technologies, and the initial cost gaps for sector coupling technologies. The higher the subsidy rates, the stronger is the increase in power generation both by renewable power generation as well as by fossil-based power generation as long as the RPS remains binding. As laid out above, changes in the ratio of supply elasticities between power from fossils and power from renewables can lead to sign changes of demand-side subsidies (*sub-OEC*) regarding the REC price and, thus, the stringency of the RPS. Finally, the higher the initial cost cap for sector coupling technologies, the less effective are both subsidies to power generation from renewables and direct subsidies to clean technologies in the OEC sector for substituting dirty energy use and reducing emissions in the OEC sector.

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 nearly €30 billion in 2022 alone.[19] 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

[18] To further clarify the relation between the above discussion of elasticities and condition (15) in the theoretical analysis, let $\varepsilon_j = \frac{p}{q_j}\frac{dq_j}{dp}, j = c, d$ be the supply elasticities for producing electricity with the dirty (d) fossil and the clean (c) renewable technology. Noting that the supply curve can be approximated by the upward-sloping portion of the marginal cost curve $C_j'(\cdot)$, we have $\frac{dp}{dq_j} = C_j''(\cdot)$. Hence $\varepsilon_d > \varepsilon_c \iff \frac{p}{q_d}\frac{1}{C_d''(\cdot)} > \frac{p}{q_c}\frac{1}{C_c''(\cdot)} \iff C_c''(\cdot) - \frac{1-r}{r}C_f''(\cdot) > 0$, where we have used $\frac{q_d}{q_c} = \frac{q_c+q_d}{q_c} - 1 = \frac{1-r}{r}$ in the last step.

[19] 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/figures/auctioning-revenues-and-reported-usage-1 (permalink 3dc94b996fb24314b2771b90224cf06f) for data on revenues from auctioning EU ETS allowances.

is often captured with the analogy of a waterbed effect, where avoided emissions pop up elsewhere. Accordingly, 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 a quantity instrument in the electricity sector (ETS or RPS) with complementary regulatory 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 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 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" if the electricity sector is regulated by an ETS. 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. Many countries aim to increase the share of renewable energies as well as that of BEVs. Cancelling ETS allowances in the electricity sector achieves the first goal, but — by rising electricity prices — negatively impacts the second. By contrast, cancelling allowances in a separate emissions trading systems (ETS2) for 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. In policy discussions, but also in the economics literature, this happens rarely so far.

The relevance of sector coupling for the impact of emission reduction policies is by no means limited to the EU ETS, which served as the main example to motivate our analysis. A similar situation is arising in China, where the emerging national ETS for the electricity sector — the world's largest in terms of emissions covered (World Bank, 2024)— overlaps with existing regional ETS that also cover transport and buildings, such as the ETS in Shanghai. Another prominent example is the Regional Greenhouse Gas Initiative (RGGI) that covers 11 Eastern States of the US.

Other quantity instruments like renewable portfolio standards (RPS) are also affected by sector coupling. To demonstrate this, we analyzed a regulatory framework similar to the situation in the US, where subsidies under the Inflation Reduction Act overlap with a RPS that exists in many states. We find that subsidies for renewable energies in the electricity sectors dilute the RPS, whereas subsidies in the OEC sectors often have the opposite effect due to sector coupling, especially when the RPS is already stringent.

There are many other interesting impacts of sector coupling on emission reduction policies. For example, although support policies for renewable energies are largely ineffective for reducing emissions in the ETS sector, they lower the emissions 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. Similarly, the CO_2 tax level to achieve a certain emissions reduction target in the electricity sector rises if power-to-X technologies are subsidised. In summary, the economics of sector coupling lead to a large research agenda that is 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 $i \in N$:

$$u_i'(y_i) = C_{di}'(y_{di}) + \psi_i, \tag{16}$$
$$u_i'(y_i) = C_{ci}'(y_{ci}) - \lambda_i, \tag{17}$$
$$u_i'(x_i) = C_{di}'(x_{di}) + \kappa_i, \tag{18}$$
$$u_i'(x_i) = C_{ci}'(x_{ci}) + \beta\,[C_{ci}'(y_{ci}) - \lambda_i] - \sigma_i, \tag{19}$$

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

$$u_i''(y_i)dy_i = C_{di}''(y_{di})dy_{di} + d\psi_i, \tag{20}$$
$$u_i''(y_i)dy_i = C_{ci}''(y_{ci})dy_{ci} - d\lambda_i, \tag{21}$$
$$u_i''(x_i)dx_i = C_{di}''(x_{di})dx_{di} + d\kappa_i, \tag{22}$$
$$u_i''(x_i)dx_i = C_{ci}''(x_{ci})dx_{ci} + \beta\,[C_{ci}''(y_{ci})dy_{ci} - d\lambda_i] - d\sigma_i. \tag{23}$$

Moreover, total differentiation of the market clearing conditions (11) and (12) for x_i and y_i yields

$$dx_i = dx_{di} + dx_{ci} \text{ and } dy_i = dy_{di} + dy_{ci} - \beta dx_{ci},\ i \in N, \tag{24}$$

and after summing up the terms

$$\sum_{i\in N} dx_i = \sum_{i\in N} dx_{di} + \sum_{i\in N} dx_{ci} \quad \text{and} \quad \sum_{i\in N} dy_i = \sum_{i\in N} dy_{di} + \sum_{i\in N} dy_{ci} - \beta \sum_{i\in N} dx_{ci}, \quad i \in N. \tag{25}$$

The proofs are based on evaluating this system of equations (20) to (24) that determines the comparative static effects of the policy intervention (represented by $\psi_i, \lambda_i, \kappa_i$, and σ_i) on the endogenous variables. If there exist an emissions trading system, then total differentiation of the market clearing conditions (13) and (14) for their allowances yields the additional equations:

$$\text{for the ELE sector:} \quad \alpha_y \sum_{i\in N} dy_{di} = 0, \tag{26}$$

$$\text{for the OEC sector:} \quad \alpha_x \sum_{i\in N} dx_{di} = -d\zeta. \tag{27}$$

Finally, due to the strict concavity of utility and the strict convexity of the cost functions, $u_i''(\cdot) < 0$ and $C_{ci}''(\cdot), C_{di}''(\cdot) > 0$. Hence, Eq. (21) immediately implies

$$\text{sign}(dy_{ci}) = -\text{sign}(dy_i) \text{ for all } i \in N \text{ if } d\lambda_i = 0, \tag{28}$$

i.e., for all cases except the RPS.

A.1 Proof of Proposition 1

The comparative static effects in the proposition must satisfy the equations system (20) to (26) for $d\psi_i = \alpha_y d\nu$ and $d\lambda_i = 0$, as well as either $d\kappa_A = \alpha_x d\tau_A > d\kappa_j = 0$ (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 (26) 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 (20), case (ii) implies $dy_B > 0$ so that $dy_{cB} < 0$ (from 28). Hence (24) can only be satisfied if $dx_{cB} < 0$. Noting that $d\sigma_B = d\tau_B = 0$, from (23) and $u_i''(x_i) < 0$ we obtain $dx_B > 0$ so that $dx_{dB} < 0$ (from 22). However, using $dx_{cB} < 0$ this cannot satisfy (24); 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 20). Hence $dx_{cA} \leq 0$ (from 24) so that $dx_A \geq 0$, where the inequality is strict for the subsidy case with $d\sigma_A > 0$. Therefore, condition (22) 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 (24). 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 (20) and $d\nu > 0$ we then have $dy_B < 0 \Longrightarrow dy_{cB} > 0$ so that $dx_{cB} > 0$ (from 24) and $dx_B < 0$ (from 23). This in turn implies $dx_{dB} > 0$ (from 22) so that (24) is violated. Hence we conclude that $dy_{dj} < 0 \; \forall \; j \in N\backslash A$ which from (26) immediately implies $dy_{dA} > 0$.

Using $d\nu > 0$ and $dy_{dA} > 0$, it follows from (20) that $dy_A < 0 \Longrightarrow dy_{cA} > 0$, which in turn requires $dx_{cA} > 0$ to satisfy (24). 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 22), which cannot satisfy (24). Hence we have a contradiction and conclude that $dx_A > 0$, which implies $dx_{dA} < 0$ (from 22).

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 $dy_{dj} < 0$, (24) requires $dx_{cj} < 0$ so that $dx_j > 0$ (from 23) and $dx_{dj} < 0$ (from 22), which cannot satisfy (24). 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 (22) and $dx_{cj} < 0$ (from (23) and $dy_{cj} > 0$), which cannot satisfy (24). Therefore, $dx_j < 0$, which implies $dx_{dj} > 0$ (from 22) so that $dx_{cj} < 0$ (from 24).

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 (25) and (26) imply $\sum_{i \in N} dx_{ci} > 0$. 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

As there is an ETS2 in the OEC sector, the market clearance condition for that allowance market also has to be taken into account so that the comparative static effects now follow from the system of equations (20) to (27) for $d\psi_i = \alpha_y d\nu, d\kappa_i = \alpha_x d\varphi$, and $d\lambda_i = d\sigma_i = 0 \; \forall \; i \in N$.

By contradiction to the proposition, assume $d\varphi \leq 0$ and note that due to the cancellation of allowances in the ETS2 there must be countries (at least one), indexed j, for which $dx_{dj} < 0$. For them, $dx_j > 0$ from (22) so that $dx_{cj} > 0$ from (24). Using this, (23) requires $dy_{cj} < 0$ so that $dy_j > 0$ from (28). Hence $dy_{dj} > 0$ from (24) and $d\nu < 0$ from (20).

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 (20) and, thus, $dy_{di} > 0$ for all $i \in N$. This violates (26) 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 (25) and (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 23), which violates (24). 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 22), $dx_{ck} < 0$ (from 24), $dy_{ck} > 0 \Longrightarrow dy_k < 0$ from (23), $dy_{dk} < 0$ (from 24), and, thus, $d\nu > 0$ from (20). 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 20). It follows that $dx_{cj} > 0$ (from 24) and $dx_j < 0$ (from 23).

Note that all countries have the common terms $\alpha_y d\nu$ and $\alpha_x d\varphi$. Hence subtraction of the expressions (20) for countries of types j and k, and doing the same with (21) yields

$$u_j''(y_j)dy_j - u_k''(y_k)dy_k = C_{dj}''(y_{dj})dy_{dj} - C_{dk}''(y_{dk})dy_{dk} = C_{cj}''(y_{cj})dy_{cj} - C_{ck}''(y_{ck})dy_{ck} > 0, \quad (29)$$

where the sign follows from $dy_{dj} > 0$ and $dy_{dk} < 0$. Similarly, subtraction of the expressions (22) and (23) for countries of types j and k yields

$$C_{dj}''(x_{dj})dx_{dj} - C_{dk}''(x_{dk})dx_{dk} = C_{cj}''(x_{cj})dx_{cj} + \beta C_{cj}''(y_{cj})dy_{cj} - C_{ck}''(x_{ck})dx_{ck} - \beta C_{ck}''(y_{ck})dy_{ck} < 0, \quad (30)$$

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 (29), the sign of (30) 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 (20) we obtain $dy_j \geq 0 \implies dy_{cj} \leq 0$ so that $dx_{cj} < 0$ (from 24), which in turn implies $dx_j > 0$ (from 23) and $dx_j < 0$ (from 24), a contradiction. We conclude that $\nu > 0$.

Using this and $dy_{dk} \geq 0$ for k-type countries, $dy_k < 0 \implies dy_{ck} > 0$ (from 20) so that $dx_{ck} > 0$ (from 24) and, thus, $dx_k < 0$ (from 23). By contrast, from (20) 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 $dy_i < 0 \implies dy_{ci} > 0$ for all $i \in N$. Moreover, suppose there was a j-type country with $dx_j \geq 0$. Then $dx_{cj} < 0$ (from 23) so that $dx_j < 0$ from (24), a contradiction. We conclude that $dx_i < 0$ for all $i \in N$. Finally, note that neither (23) nor the two expressions in (24) allow us to fix the sign of dx_{cj}. Nevertheless, $\sum_{i\in N} dx_{ci} > 0$ (from 25).

A.4 Proof of Proposition 4

If ρ allowances are cancelled in the ETS of the ELE sector, the market clearance condition for that allowance market becomes $\alpha_y \sum_{i\in N} dy_{di} = -\rho$, which after total differentiation yields

$$\alpha_y \sum_{i\in N} dy_{di} = -d\rho. \quad (31)$$

Moreover, no allowances in the ETS2 are cancelled so that $\sum_{i\in N} dx_{di} = 0$. Using this and (31) (instead of the corresponding condition (26)), the result $d\varphi > 0$ follows from the same steps as in the beginning of the proof of Proposition 3. 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 ETS2. Using $d\varphi > 0$, for all such countries we obtain $dx_k < 0$ from (22), $dx_{ck} < 0$ from (24), $dy_{ck} > 0 \implies dy_k < 0$ from (23), $dy_{dk} < 0$ from (24), and, thus, $d\nu > 0$ from (20).

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 (29) and (30) 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 (30) is still strictly negative. Moreover, we have already shown that $dy_{dk} < 0$;

hence assuming $dy_{dj} \geq 0$ expression (29) 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 (29), the sign of (30) 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 (24). 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 (24) this requires $dx_{cj} < 0$ so that (24) implies $dx_j < 0$, whereas (23) 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 (24) 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 (23), also for them $dx_j < 0$. We conclude that $dx_i < 0$ for all $i \in N$, which from (25) and $\sum_{i \in N} dx_{di} = 0$ implies that $\sum_{i \in N} dx_{ci} < 0$. Finally, using this and $dy_i < 0 \;\forall\; i \in N$, rearranging the second expression in (25) yields $\sum_{i \in N}(dy_{di} + dy_{ci}) = \sum_{i \in N}(dy_i + \beta dx_{ci}) < 0$.

A.5 Proof of Proposition 5

With an RPS, the comparative static effects follow from the system of equations (20) to (24) for $d\psi_i = \frac{r_i}{1-r_i} d\gamma_i, d\lambda_i = d\gamma_i + ds_i, \kappa_i = 0$ (see Table 1) and

$$dy_{di} = \frac{1 - r_i}{r_i} dy_{ci}, \tag{32}$$

which follows from the definition of the renewable portfolio standard and implies $\text{sign}(dy_{di}) = \text{sign}(dy_{ci})$. Moreover, using $dx_i = dx_{di} + dx_{ci}$ and noting that from (22) dx_i and dx_{di} must have the opposite sign for $\kappa_i = 0$, we obtain

$$\text{sign}(dx_i) = \text{sign}(dx_{ci}) = -\text{sign}(dx_{di}). \tag{33}$$

First, consider an increase of the subsidy in the electricity sector, i.e, $ds_i > 0, d\sigma_i = 0$. By contradiction to the statement in (a), suppose that $d\gamma_i \geq 0$. There are two cases. If $dy_{ci}, dy_{di} > 0$, we have $dy_i < 0$ (from 20), which implies $dx_{ci} > 0, dx_i > 0, dx_{di} < 0$ (from 24 and 33). Noting that the right-hand side of (21) is strictly positive, this violates (23) for $d\sigma_i = 0$. Alternatively, suppose $dy_{ci}, dy_{di} \leq 0$ so that $dy_i > 0$ (from 21). Using this, $dx_{ci} < 0, dx_i < 0, dx_{di} > 0$ (from 24 and 33), which again violates (23). Thus, $d\gamma_i \geq 0$ always yields a contradiction and we conclude that $ds_i > 0, d\sigma_i = 0$ leads to $d\gamma_i < 0$.

Using this when analyzing the results in statement in (b), assume by contradiction that $dy_{di}, dy_{ci} \leq 0$. Hence $dy_i > 0$ (from 20), which implies $dx_{ci} < 0, dx_i < 0, dx_{di} > 0$ (from 24 and 33), violating (23). Accordingly, $dy_{di}, dy_{ci} > 0$. Moreover, assuming $dy_i \leq 0$ implies $dx_{ci} > 0, dx_i > 0, dx_{di} < 0$ (from 24 and 33), which cannot satisfy (23). Hence $dy_i > 0$ so that $dx_i \leq 0$ leads to a contradiction by the usual steps. Therefore, $dx_i > 0, dx_{di} < 0, dx_{ci} > 0$. Finally, $dp_{yi}, dp_{xi} < 0$ as they have the opposite sign of $dy_i, dx_i > 0$ (from total differentiation of 9 and 10).

Next, consider an increase of the subsidy in the OEC sector, i.e, $ds_i = 0$,$d\sigma_i > 0$ and assume, by contradiction, that $dx_{ci} \leq 0$ so that $dx_i \leq 0, dx_{di} \geq 0$ (from 33). Thus (23) requires $C''_{ci}(y_{ci})dy_{ci} - d\gamma_i >$

0 so that $dy_i < 0$ (from 21). Hence $dy_{ci}, dy_{di} < 0$ (from 24) which requires $d\gamma_i > 0$ from (20) and $d\gamma_i < 0$ from (21), a contradiction. We conclude that $dx_{ci} > 0, dx_i > 0, dx_{di} < 0$. Next suppose $dy_i \geq 0$, which from (24) requires $dy_{ci}, dy_{di} > 0$. Therefore, $d\gamma_i < 0$ from (20) and $d\gamma_i > 0$ from (21), a contradiction. We conclude $dy_i < 0$. If $dy_{ci}, dy_{di} \leq 0$, (20) and (21) can again not be satisfied as they would require the opposite sign of $d\gamma_i$. Therefore, $dy_{di}, dy_{ci} > 0$ and it only remains to determine the sign of $d\gamma_i$.

Noting that the right-hand sides of (20) and (21) must be equal, and solving this for γ_i yields

$$d\gamma_i = (1 - r_i)\left(C''_{ci}(y_{ci}) - \frac{1 - r_i}{r_i} C''_{di}(y_{di})\right) dy_{ci}. \tag{34}$$

Therefore,

$$d\gamma_i \gtreqless 0 \Longleftrightarrow C''_{ci}(y_{ci}) - \frac{1 - r_i}{r_i} C''_{di}(y_{di}) \gtreqless 0, \tag{35}$$

so that the condition in (15) determines the sign of $d\gamma_i$.

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.

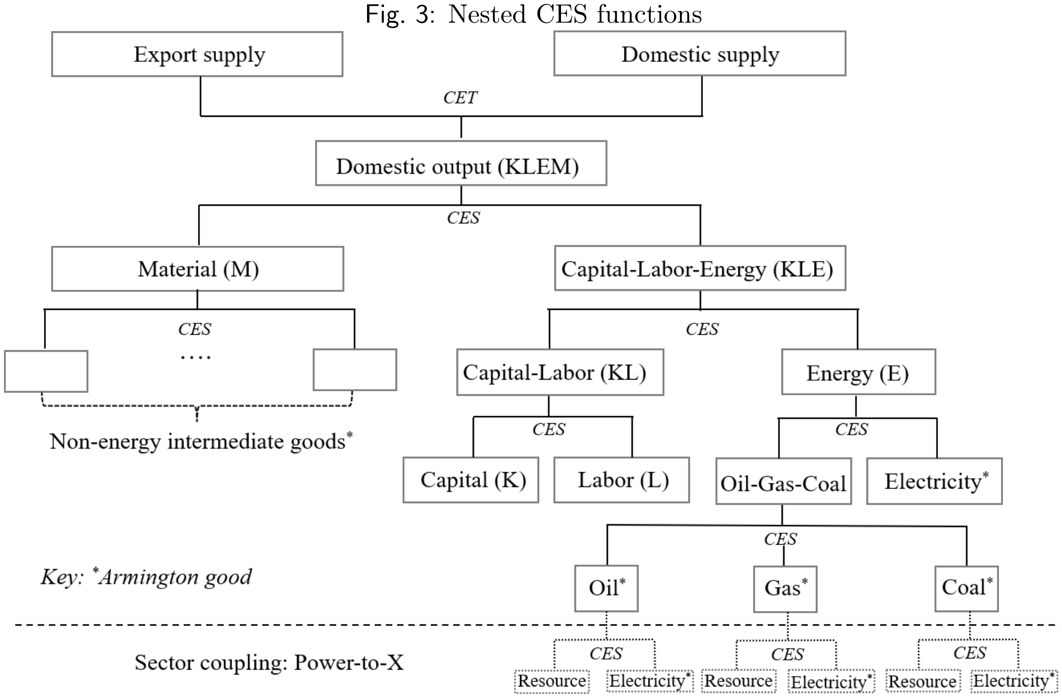
B.1 Non-technical model summary

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 labor and capital which are assumed to be mobile across sectors within each region but not internationally. Specific resources are tied to the production of fossil fuels (coal, natural gas, and crude oil) as well as electricity generation by different power technologies 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), labor (L), energy (E), and material (M). At the top level, a material composite (M) trades off with an aggregate of capital, labor, and energy (KLE). At the second level, the material composite splits into non-energy intermediate goods, whereas the aggregate of capital, labor, and energy splits into a value-added composite (KL) and the energy component (E). At the third level, capital and labor inputs enter the value-added composite subject to a constant elasticity of substitution. Likewise, within the energy aggregate, electricity trades off with 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.

Fig. 3: Nested CES functions



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 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_{ir}^{u} 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 7. 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 ($i \notin FF$)

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

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

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

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

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

3. Armington aggregate

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

4. Import aggregate

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

B.2.2 Market-clearance conditions[20]

5. Labor

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

6. Capital

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

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

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

[20] Market-clearance conditions are stated with supplies on the left-hand side and demands on the right-hand side. Hence, should the equilibrium 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)[21]

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

[21] 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 so that the aggregate term drops out from the market clearance condition of the composite consumption in the numeraire region.

Tab. 7: 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

Tab. 7: Notations for variables

σ_{ir}^{KL}	Labor and capital in the value-added composite of sector i and region r
σ_{ir}^{Q}	Fossil fuel resources and other inputs in sector i ($i \in FF$) and region r
σ_{ir}^{ELE}	Electricity and the composite of other secondary energy goods in the energy aggregate of sector i and region r
σ_{ir}^{FE}	Energy goods in the non-electric energy composite of sector i and region r
σ_{ir}^{A}	The import composite and the domestic good variety of sector i and region r
σ_{ir}^{A}	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
	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 ($i \in FE$)

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