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Optimal allocation of the EU carbon budget: A multi-model assessment

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ABSTRACT

The European Union (EU) has pledged to reduce greenhouse gas (GHG) emissions until the year 2030 by 55% compared to 1990. Recently, the EU institutions decided to introduce a new Emission Trading System for road transport, buildings and fuels for additional sectors (ETS2) in addition to the current EU ETS. Contested design features were the split of the carbon budget between the EU ETS and the remaining sectors regulated under the Effort Sharing Regulation (ESR), and the carbon price level of the ETS2. Conducting a multi-model assessment, we find that the agreed allocation of the carbon budget between EU ETS and ESR sectors seems almost optimal from an economic efficiency point of view. We also find that if carbon prices are the only instruments used, the prices necessary to reach the emission targets range from 130 to 286 €/tCO_2 in the EU ETS and from 175 to 360 €/tCO_2 for the energy-related ESR (ESR-E) emissions – depending on technology development and baseline assumptions of the different models. Our results imply that when the ETS2 price does not go above the “indicative cap” of 45 €/tCO_2, the abatement target will not be reached with a carbon price alone. The remaining abatement needs to come from complementary policies like technology standards or subsidies. As abatement costs from these policies are above 45 €/tCO_2, effective costs for consumers could well exceed the costs of carbon pricing alone due to inefficiencies that arise from the lack of flexibility to mitigate emissions where it is cheapest.

1. Introduction

The European Union (EU) has pledged to reduce greenhouse gas (GHG) emissions until the year 2030 by 55% compared to 1990. The resulting carbon budget is allocated mainly to two different sectoral categories: First, the EU Emissions Trading System (EU ETS) regulates energy intensive industries, air, and water transport. It imposes a single cap on carbon emissions in the EU, defining the annual emission budget. Second, the Effort Sharing Regulation (ESR) regulates the remaining emissions. For these emissions there is an individual carbon budget for each member state (MS), i.e., the ESR regulates allocation of the emission budget across countries. The ESR allows, however, that MS partly trade these emission rights. Recently, the EU institutions have decided to introduce a new Emission Trading System for road transport, buildings and fuels for additional sectors (ETS2) [1].

The EU therefore had to decide how to allocate the carbon budget across sectors and MS. Two major options exist. First, extending the EU ETS to cover all sectors leading to one EU-wide cap and a uniform European carbon price. This delegates the final allocation of the fixed carbon budget across sectors, countries and installations to the market. Second, maintaining the current sectoral scopes and deciding about the respective carbon budgets for the EU ETS and the ESR sectors.

In the short term, a full European trading system is politically unlikely. Therefore, the EU decided about the carbon budget under the EU ETS and under the ESR, respectively. This decision impacts the cost of reaching the climate targets. In the original proposal, the European Commission (EC) suggested to attribute 64% of the remaining 2030 GHG emissions budget to the ESR sectors and the rest to the EU ETS.[1] According to the EC's impact assessment, this split results in EU ETS and ETS2 price estimates of around 50 €/tCO_2 for a scenario with strong

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[1] During the negotiation process, the abatement targets for the EU ETS sectors have been slightly tightened [2]. However, this change only has a minor impact on the results presented in this paper.

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additional measures in complement to carbon pricing (*MIX*) [3]. For a scenario with less stringent additional measures (*MIX-CP*) the ESR price estimate increases to 80 €/tCO_2 [3].

Current literature on optimal GHG budget allocation between ESR and EU ETS sectors shows a large bandwidth of outcomes. Zaklan et al. [4] calculate a Non-ETS budget share of ca. 47% in 2030 by aiming for equal marginal abatement costs across countries and sectors. Abrell and Rausch [5] simulate consumption losses from stronger EU climate targets with a CGE model. According to their results, consumption losses in 2030 are minimal at a Non-ETS budget share of 80% and a CO2 price of around 100 €/t. Kattelmann et al. [6] arrive at an optimal Non-ETS budget share of 61% in 2030 using the energy system model TIMES-PanEU. Pietzcker et al. [7] calculate that a Non-ETS budget share of 67% would equalize the required carbon prices in ETS and ESR sectors.

Given the multitude of factors and assumptions that influence the optimal budget allocation and carbon prices, such an assessment should indeed be grounded on multiple model assessments covering a broad range of methodological, technological, and behavioral assumptions. We thus conduct a multi-model assessment using four different models to put the EC's proposal in perspective by addressing the two questions: First, what is the optimal allocation of the EU carbon budget to EU ETS and ESR sectors? Second, what are the resulting carbon prices? Our answer to these questions is not a number, but a range representing best guesses based on different approaches.

As several of the models contributing to this study focus exclusively on CO_2 emissions, we convert the EC's proposed GHG-based ESR share of 64% into an *energy-related* CO_2-based ESR-E share of 62–63%. This implies that our ESR-E sector has a rather high overlap with the actual ETS2 sectors. We find that optimally between 60 and 70% of the total carbon budget should be allocated to the ESR-E sectors. The EC's choice of 62–63% thus lies at the lower end of the optimal allocation. However, our assessment also shows that within a range of around 55–70%, varying the split between ESR-E and EU ETS shares does not significantly affect total welfare.

Regarding the second question, for the proposed split of the carbon budget, our models provide EU ETS price estimates of 130–286 €/tCO_2 that would be necessary to reach the emission targets in the absence of new additional policies. For the ESR-E sectors, carbon prices between 175 and 360 €/tCO_2 would be necessary to reach the targets if a carbon price is the only new instrument used to reach the target. These price estimates depend on technology development and baseline assumptions of the different models. However, they all clearly lie above the EC's estimates of 50–80 €/tCO_2. Importantly, we assume that MS trade their carbon budgets, i.e., countries do not necessarily reach their individual ESR targets but the EU-wide ESR target is met. This assumption implies that trade of Annual Emission Allocations (AEA) between MS works without constraints. However, in practice, AEA trade seems to face significant political barriers, leading to heterogeneous carbon prices across MS and, thus, higher total abatement costs [8].

Our results have two implications for the policy debate: First, if the "indicative" ETS2 price cap of 45 €/tCO_2 [9] would be attained through the stability mechanisms underpinning it, the abatement target cannot be reached with a carbon price alone. The remaining abatement requires stringent complementary policies like technology standards or subsidies. As abatement costs from these policies are above 45 €/tCO_2, effective costs for consumers could well exceed the costs of a higher carbon price. This would result from inefficiencies that can arise from the lack of flexibility to mitigate emissions where it is cheapest. Second, shifting the budget between EU ETS and ESR sectors in the discussed range has a relatively low impact on overall welfare, given current knowledge about abatement costs.

This paper proceeds as follows: In the next section, we introduce the numerical approach and describe models and scenarios, Section 3 presents the CO2-price ranges across models, in Section 4 we discuss the optimal allocation of the EU carbon budget. Section 5 concludes.

2. Numerical approach

We use four different models to examine the cost implications of allocating the EU carbon budget between the EU ETS and the ESR-E sectors. The models differ in several dimensions including the model type and assumptions on technological developments, energy efficiency potentials, political measures along the baseline path and GHG reduction targets for Non-EU-regions (see Tables 1 and 2 in Appendix). We interpret these differences as uncertainty about future outcomes and therefore do not aim to harmonize these assumptions. Besides the scenario specifications and harmonization of outcome measures to ensure comparability of the results, we thus keep model harmonization at a minimum.

2.1. Models

We use four different models[2]:

- REMIND-EU (Regional Model of Investments and Development; [7,10,11]) is a global multi-regional energy-economy-climate model combining an economic growth model with detailed modelling of the energy, agriculture, and climate system.
- TIMES-PanEU is a multi-regional model containing all countries of the European Union of 27 Member States (EU27) and UK, Switzerland and Norway. The model minimizes an objective function representing the total discounted system costs over the time horizon from 2010 to 2050 and assumes perfect competition among different technologies and pathways of energy conversion [6,12,13].
- NEWAGE (National European Worldwide Applied General Equilibrium; [14,15]) is a global recursive-dynamic multi-region Computable General Equilibrium (CGE) model. It represents electricity production in a detailed manner using discrete generation technologies. Data sources include GTAP 10 [16], EXIOBASE 3 [17], various IEA data and others.
- ZEW CGE [5] is a global static multi-region CGE model. It represents electricity production in a detailed manner using discrete generation technologies.

2.2. Scenarios

We examine the cost implications of allocating the EU carbon budget between the EU ETS and the ESR-E sectors in a common scenario framework. In all scenarios, we implement the 2030 target of 55% GHG reduction compared to 1990. We vary the allocation of the carbon budget between the EU ETS and ESR-E by varying the share of the ESR-E in the total EU carbon budget. We assume carbon trading under the EU ETS and under the ESR-E leading to two European carbon prices. In addition to the EU ETS/ESR-E system, we also model a *Fulltrade* scenario as reference point. The *Fulltrade* scenario implements a single EU carbon trading system resulting in a single carbon price.

3. CO_2-price ranges across models

Fig. 1 shows carbon prices for the EU ETS and the ESR-E sectors depending on the share of the carbon budget allocated to the ESR-E sectors. The higher this share in the budget split, the more abatement needs to take place in the EU ETS sectors. As expected, the EU ETS prices (left panel) increase and ESR-E prices (right panel) decrease with a

[2] Detailed model overviews can also be found in the Scenario Report of Kopernikus-Projekt Ariadne (2021) (German only): https://ariadneprojekt.de/media/2021/10/Ariadne_Szenarienreport_Oktober2021_Appendix_Modellbeschreibungen.pdf. Descriptions of NEWAGE and TIMES-PanEU can also be found under www.ier.uni-stuttgart.de/en/research/models/NEWAGE/and www.ier.uni-stuttgart.de/en/research/models/times/.

Relation of Scenarios and Policy Proposals

While the models used in our analysis are well suited to assess the fundamental design choices of the recent policy debate, they are not in all aspects an accurate reflection of the political reality. In particular, the following points need to be kept in mind for the interpretation of our results:

- *Sectoral and GHG coverage:* The analysis focuses on energy-related CO2-emissions, i.e., we abstract from non-energy-related CO2 as well as other GHG emissions. This implies that our ESR-E sector has a high overlap with the ETS2 sectors, which covers buildings, road transport and additional sectors, which correspond to industrial activities not covered by the EU ETS (European Commission 2021; European Parliament 2022; Göss 2023, European Council 2023b). Furthermore, it has been decided that by 2026 the EU ETS will cover all maritime shipping emissions. This sectoral extension is not yet reflected in our models.
- *Complementary instruments:* In our scenarios, carbon prices are the only new instrument to reach the 2030 targets. They are implemented mimicking cap-and-trade systems, i.e., we impose a quantitative limit on emissions and the models endogenously determine the according carbon price. Other than that, we do not implement additional policies to achieve the emission reduction relative to the baseline of the respective model. Some models, however, include additional policies in their baseline projection. Thus, part of the differences in results are driven by more optimistic baseline (policy) assumptions (see Appendix).
  Carbon trading is likely continued to be supplemented by accompanying measures such as renewable support schemes, energy efficiency measures, and transport policies. The absence of additional policy measures in our scenarios has thus strong implications for the interpretation of our carbon prices: They should be regarded as implicit carbon prices or, likewise, marginal abatement cost. Complementary measures in the form of technology standards or subsidies would thus reduce these carbon prices but increase total abatement costs due to inefficiencies that arise from the lack of flexibility to mitigate emissions where it is cheapest.
- *AEA trade:* In our analysis we assume that countries make use of the existing flexibility option to trade their Annual Emission Allocation (AEA). I.e., countries that overachieve their annual ESR-targets sell their allowance surplus to countries that miss their targets. This is beneficial from an economic efficiency point of view as emissions are reduced where it is cheapest. This assumption also implies that in our models, AEA trade under the ESR-E leads to an equivalent abatement outcome as the ETS2 (assuming they cover the same sectors). However, in practice, AEA trade faces significant barriers, leading to heterogeneous carbon prices across MS and higher total abatement costs (Görlach et al. 2022).

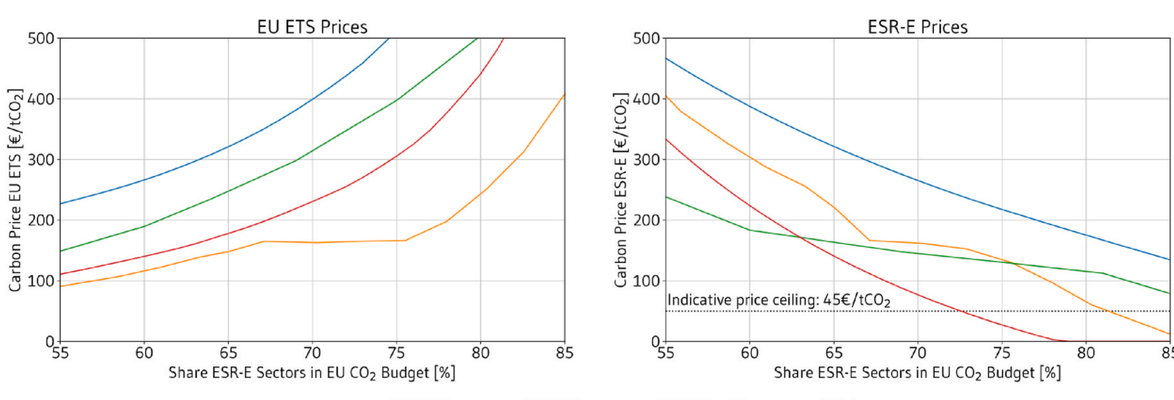

Fig. 1. Carbon prices in 2030 in EU ETS and ESR-E sectors Note: Own calculations. Graphs show implicit carbon price (y-axis measured in $€_{2021}/tCO_2$), i.e., marginal abatement cost, of EU ETS (left panel) and ESR-E (right panel) depending on the allocation of the 2030 EU carbon budget (x-axis). The budget allocation is expressed as the share of energy-related carbon allocated to the ESR-E sectors. Moving from the left to right therefore corresponds to a reallocation of the carbon budget from the EU ETS to the ESR-E and, therefore, increases (decreases) the EU ETS (ESR-E) abatement effort. The black dotted line indicates the price ceiling as agreed by the EU institutions.

higher ESR-E budget. The black dotted line indicates the price ceiling as decided.

Fig. 2 shows the model results for the budget allocation proposed by the EU commission. The EU ETS prices range from 130 to 286 €/tCO_2, whereas ESR prices lie between 175 and 360 €/tCO_2.

The results lead to two main insights: First, our EU ETS and ESR-E price estimates lie well above the 50 to 80 €/tCO_2 that are reported by the EC's impact assessment. This price difference can partly be explained by the fact that the impact assessment includes a broad range of additional policies whereas our models focus on carbon pricing. As the stringencies of complementary policies essentially depend on the individual Member States, there is a strong chance, that – in the absence of a price cap - prices would be higher than currently reported by the Commission. However, if the ESR-E price is capped at 45 €/tCO_2 as decided, substantial abatement has to come from complementary policy measures such as technology standards or subsidies in order to sufficiently reduce emissions in the ESR-E sectors.

Second, the low price difference between EU ETS and ESR-E prices at the proposed budget split indicates that the gains of carbon trade between ESR-E and EU ETS sectors are limited. This implies that the proposed split of carbon budgets between sectors is relatively well chosen.

In the next section, we analyze the potential welfare gains of different budget allocations in detail.

4. Optimal allocation of the EU carbon budget

Fig. 3 provides the EU ETS and ESR-E carbon price depending on the carbon budget allocation together with the welfare measure of the respective model. Whereas the CGE models (NEWAGE, ZEW CGE) directly provide economic welfare, REMIND reports the gross domestic product (GDP) and TIMES-PanEU reports energy system cost. Since demand in TIMES-PanEU is constant, changes in cost are equivalent to changes in economic welfare. Welfare changes are measured relative to the *Fulltrade* scenario which implements a uniform carbon price across the EU and, therefore, provides an indicator for the regulatory approach with lowest abatement cost.[3] From these results we can derive the following three main insights:

First, CO_2 prices under *Fulltrade* range from 163 €/tCO_2 to 321 €/tCO_2. Again, they are significantly higher than the prices reported by the EC.

Second, under the *Fulltrade* scenario, the models allocate between 60% and 70% of the EU's carbon budget to the ESR-E sectors. Therefore, the proposed budget split of 62–63% is at the lower end of this range.

Third, the relatively flat cost curves indicate that a slight variation in the allocation of carbon budgets between EU ETS and ESR-E sectors has no major consequences on welfare. This implies that slight changes of the split of several per cent do not significantly affect welfare. However, when more than around 70% of the total budget is allocated to the ESR-E budget, EU ETS prices start to increase more steeply,[4] reducing welfare substantially.

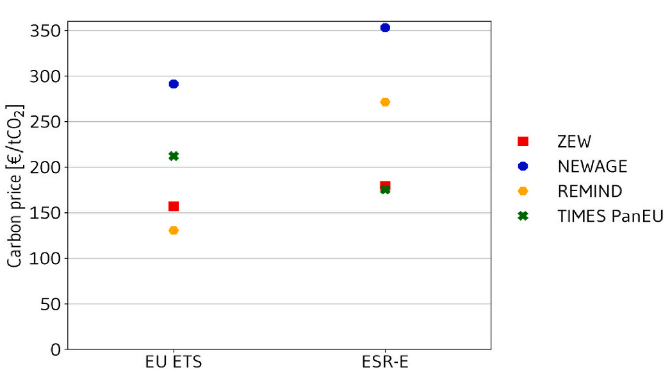

Fig. 2. Carbon prices in 2030 in EU ETS and ESR sectors for the EC's proposed budget split Note: Own calculations. The graph shows implicit carbon prices (left axis measured in €$_{2021}$/tCO_2) of each model for the EU ETS (left) and the ESR-E (right panel) sectors under the budget allocation as agreed by the EU institutions, i.e., about 62–63% of energy related carbon emissions.

5. Conclusion

We provide a multi-model assessment of the allocation of the carbon budget to EU ETS and ESR-E sectors based on four models. The models used are not in all aspects an accurate reflection of the political reality, but offer a variety of well-suited approaches to fundamentally asses carbon budget distributions. We find that the emission share allocated to the ESR-E sectors of around 62–63% (64% based on total GHG emissions) proposed by the Commission is at the lower end of the optimal range determined by the models. Yet, none of the models shows a major welfare loss for the decided budget split compared to the optimal split. More explicitly, in our modelling framework, the welfare cost of a separated EU climate policy relative to a uniform carbon price are surprisingly invariant to the allocation of the EU carbon budget.

For the budget allocation as proposed by the EC, our models show an EU ETS price range from 130 to 286 €/tCO_2 and an ESR-E price range of 175–360 €/tCO_2. These ranges are well above prices reported by the EC.

This has several implications for the policy debate: First, to the extent that the "indicative" ETS2 price cap of 45 €/tCO_2 will actually be attained, more stringent complementary policies will be needed to reach the target. While in this case the observed carbon prices will be relatively low, the total abatement costs for consumers will be even higher due to inefficiencies that arise from the lack of flexibility to mitigate emissions where it is cheapest. Second, the agreed allocation of the carbon budget between EU ETS and ESR sectors seems almost optimal from an economic efficiency perspective. Finally, welfare effects are relatively invariant to smaller shifts in the budget split. Thus, if further adjustments are needed in the course of the future negotiations, the effect on overall welfare would be small.

Future research should closely follow the political developments. Realism could be increased, for example, by modelling complementary policy instruments and including GHG other than energy-related CO_2.

CRediT authorship contribution statement

Jan Abrell: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Markus Blesl:** Supervision, Project administration. **Ulrich Fahl:** Writing - review & editing, Supervision, Project administration. **Lena Kittel:** Data curation. **Mirjam Kosch:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Gunnar Luderer:** Supervision, Project administration. **Drin Marmullaku:** Software, Investigation, Data curation, Writing - review & editing. **Michael Pahle:** Writing - review & editing, Supervision, Project administration. **Robert Pietzcker:** Software, Investigation, Data curation, Writing - review & editing. **Jonathan Siegle:** Software, Investigation, Data curation, Writing - review & editing.

[3] For models that implement commodity and/or income and/or final energy taxation (NEWAGE, ZEW CGE, REMIND), the optimal, i.e., least cost solution, might slightly deviate from the *Fulltrade* scenario due to tax interaction effects (e.g., Refs. [18,19])

[4] In the case of REMIND, the steep increase in prices only starts when more than 75% of the carbon budget are allocated to the ESR-E sectors.

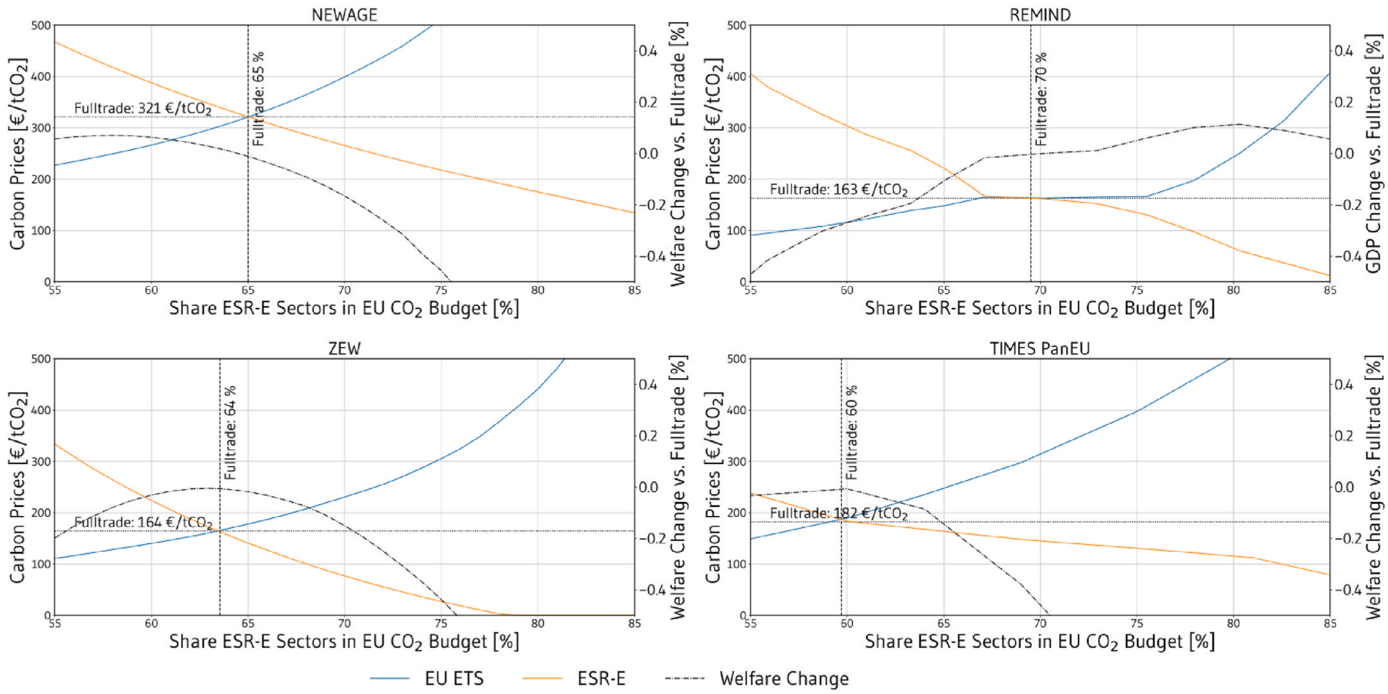

Fig. 3. Optimal split between ESR and ETS sectors Note: Own calculations. The graphs show implicit carbon prices (left axis measured in €$_{2021}$/tCO_2) for the EU ETS (blue line) and the ESR-E (orange line) depending on the allocation of the EU energy-related carbon budget (x-axis) for each model. The right axis measures the welfare cost of deviating from a single EU carbon price uniform across all sectors (black dash-dotted line). The horizontal dotted line shows the respective EU-wide uniform carbon price (fulltrade). The vertical dotted line depicts the carbon budget allocation under this uniform price. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Model characteristics.

Table A1: Model characteristics.

Model	Base year	Dynamics	Regional coverage	GHG coverage	Sectoral coverage
NEWAGE	2014	Recursive Dynamic in 5-year steps	18 regions: Germany, France, Italy, Poland, Spain+Portugal, Benelux, Northern EU (Sweden, Finland, Denmark, Latvia, Estonia, Lithuania, Ireland), South-Eastern EU (Austria, Czechia, Slovenia, Slovakia, Hungary, Croatia, Greece, Cyprus, Malta, Bulgaria, Romania), UK, USA, China, India, Russia, Brazil, South Africa, OPEC and Arabic World, Rest of OECD, Rest of World	Energy related CO2 Emissions	25 sectors: (Air Transport, Water Transport, Other Transport, Refined oil, Crude Oil, Coal, Natural Gas, Electricity, Paper and pulp and print, Glass, Cement, Rest of non-metallic minerals, Aluminum, Copper, Rest of non-ferrous metals, Vehicles, Chemistry, Iron and Steel, Machinery, Food and tobacco, Buildings, Agriculture, Services, Dwellings, Rest of industry)
REMIND	2010	Perfect foresight, 2005-2150 in 5-year steps	EU split into 9 subregions, 12 further regions to cover the world	Kyoto Gases; all energy-related emissions from transport/buildings/ industry, industry process emissions; CH_4/N_2O/CO_2 from agriculture, land use, land use change;	Transport, Buildings, Industry, Energy supply
TIMES PanEU	2005	Perfect foresight, 2010-	All EU member states, UK, Switzerland, Norway	Energy and process related emissions of CO_2, CH_4 and N_2O and agriculture; waste not considered.	Industry, Residential, Commercial, Transport, Agriculture, Electricity

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(*continued*)

Model	Base year	Dynamics	Regional coverage	GHG coverage	Sectoral coverage
		2050 in 5-year steps			
ZEW CGE	2014	No	All EU member states with Luxemburg, Malta and Cyprus aggregated to one region. Rest of OECD, Brazil, China, OPEC, Russia, South Africa, India, USA, Rest of World	Energy related CO_2 Emissions	Agriculture, energy intensive industries, Manufacturing, transport, services, coal/gas/oil extraction, refined oils, electricity generation (using discrete generation technologies)

Table A2: Base year and scenario assumptions.

Model	Energy efficiency	Policies baseline/base year	Inertia of transformation	Electricity generation technology assumptions	EU reduction 2030 vs 2005 [%]	EU GHG budget 2030 [MtCO2eq]	Reduction targets other Countries
NEWAGE	Exogenous AEEI/ Energy Productivity improvements [20]	Nuclear power phase out in Germany after 2020, other non-price-based measures	Region-specific capital with depreciation rate 4% p.a., technology-specific capital with explicit capital depreciation curves for electricity generation technologies, further assumptions	Several electricity generation limits based on various sources for generation numbers [21,23] and on assumptions regarding inertia of transformation	52.2%	1640	vs. 2014: UKI 47%, OEC 42%, USA 45%, BRZ 17%, RUS 15%, IND -49%, CHI -6%, RSA 8%, OPA -14%, ROW 8% based on International Energy Agency [24]
REMIND	Represented via CES substitution of capital against energy at the top level (capital, labor, energy)	Subsidies on Battery Electric Vehicles (BEV) in line with historic subsidies (roughly achieving the observed 2020 sales shares)	All energy supply technologies, grid, cars and trucks modeled with explicit vintages; for buildings and industry substitution is governed by CES function with substitution elasticities between 1 and 3	No hard bounds on expansion of generation technologies, but upscaling costs increase with the square of the relative increase to the last time step	50.0%	2330	global CO_2 budget from 2020 to peaking year of 900 Gt CO_2 ("well below 2 °C" scenario, reaching median peaking warming of ~1.6-1.7°C)
TIMES PanEU	Energy Saving law for buildings (EnEV as part of the GEG); parts of the energy service law (industry); reduction quotas for the fleet consumption in transport	Current state of regulatory measures: coal phase out of EU member states, biofuel quotas (until 2030), renewable energy act in residential, oil phase out in building sector after 2026	Taking into account the stocks and the lifetime, maximum of new installed capacities of renewables, security of supply and required balancing energy, building times for huge investments	Economic progress for emission free electricity generation technologies (e.q. electrolysis, fuel cells, batteries)	46.7%	2140	Switzerland and Norway GHG neutrality in 2045, UK in 2050
ZEW CGE	No exogenous energy efficiency improvements assumed	No policies except those discussed in the main text, no expansion of nuclear power.	Capital malleability for electricity generation technologies governed by CET function with transformation elasticity equal to one.	Electricity: no expansion of nuclear and hydro, "Other" technologies allowed to expand by 50%	47.7%	1523	OEC 40%, USA 44%, BRZ 33%, RUS 16%, IND -4%, CHI 25%, RSA 28%, OPA 0%, ROW 3% based on International Energy Agency [22]

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