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ORIGINAL ARTICLE

The landscape of European policies in the power sector: first-mover advantages

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Abstract
In order to achieve the commonly agreed emission reduction target, the European Commission called upon the member states to submit National Energy and Climate Plans to ensure increased transparency for the respective national targets and strategies. An analysis of these plans shows that some member states have declared ambitious emission reductions targets, as well as technology-specific phaseout policies in the power sector. A transformation to a climate-friendly system requires considerable investment, the question arises if there are benefits to be in the vanguard. We find that countries may have an incentive to outperform in the development of a low-carbon electricity system.

Keywords Electricity · Utilities · Thermal generation · Unilateral action · Climate policy

JEL classification C6 Mathematical methods · Programming models · Mathematical and simulation modeling · Q4 Electricity · Energy · Energy Utilities · Gas · Hydrocarbons

1 Introduction

The European Union (EU) has adopted an ambitious legislative framework under the Energy Union (EC 2018a) that aims to support the achievement of the EU's 2030 environmental targets and even to exceed its commitments under the Paris Agreement. As the European Commission (EC) points out (EC 2019a): "These targets are not ceilings but rather floors,

Highlights
• Despite continuous efforts toward an integrated European power system, the energy policy landscape of the member states is fragmented.
• Setting national emission reduction targets demonstrates strategic decision-making and could influence the energy policies of neighboring member states.
• First-mover advantages can be a decisive driving force for the transformation of European energy systems.

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and with the right incentives they can even be surpassed." In order to increase transparency and coordinate the planning of public and private investments, the EC required each member state to draw up a National Energy and Climate Plan (NECP) and to describe its current and planned policies and targets under five major dimensions: (I) *decarbonization* (including greenhouse gas emissions and renewable energy), (II) *energy efficiency*, (III) *energy security*, (IV) *internal energy market*, and (V) *research innovation and competitiveness* (EC 2019b).

A careful inspection of the reported NECPs reveals that some member states' targets show a significant level of ambition for emission reduction and renewable expansion. In the following, we focus on the levels of ambition in the emission reduction and technology specific phaseouts in the power generation sector. Achieving the national decarbonization targets in the electricity sector involves various technological and regulatory strategies such as increasing renewable energy production, carbon capture and storage utilization (CCSU) technologies, and expanding demand-side management potentials and smart grids. Some member states have further made political decisions to deploy or phase out particular generation technologies, such as coal-fired or nuclear power plants, decisively influencing national electricity systems.

In the light of ambitious national policies in the European landscape, two important questions arise. First, why do some member states commit to comparatively ambitious targets contributing to EU-wide adopted objectives? Second, how do such national targets affect highly interconnected electricity systems such as that of the EU?

European electricity markets are a highly integrated system with respect to both infrastructure and regulation. Developments in one market often influence neighboring markets. Hence, any analysis of one country's energy policy must consider possible effects on neighboring member states. In this study, we compare how Europe's electricity markets perform when countries broadly adhere to existing set of policies and national mitigation targets and when single countries (or country groups) aim for stricter abatement strategies as technology-specific phaseouts. We focus on national climate targets and decarbonization strategies, evaluating how electricity production structures will change and what influence they will have on greenhouse gas emissions. Finally, we attempt to identify economic reasons why individual countries would seek for more ambitious climate policies.

2 Literature and policy review

2.1 Literature review

National energy policy goals and decarbonization strategies aim to tackle challenges posed by climate change. Announced policies address various aspects of the energy sector, setting targets for energy efficiency, renewable energy expansion, and the reduction of greenhouse gas (GHG) emissions in power, buildings, transport, and industry sectors. The pace, target setting, and choice of policy instruments on national level determine the long-term effects of adaptation and mitigation measures beyond national borders. Several studies have focused on the global climate agreement and the stringency of GHG emission reduction targets and long-term mitigation efforts (Böhringer et al. 2017, Juergens et al. 2013, Paltsev 2001). These studies have analyzed the fragmented climate policy regimes emerging from unequal carbon prices across different regions of the world. The higher costs of delayed action outweigh the seemingly intuitive decision to postpone measures and thus avoid the short-term costs of more ambitious climate policy (Arroyo-Currás et al. 2015). This may explain why some countries find it beneficial to move forward unilaterally. In contrast, cooperative efforts allow the common emission reduction target to be met cost-effectively; see Weissbart (2020) for an analysis of how member states' cooperation can reduce GHG emissions to meet decarbonization targets for European electricity markets.

Hoel (1991) highlighted two possible arguments for unilateral actions to reduce emissions taken by a country. First, they are supposed to contribute—albeit only slightly—to climate protection and, second, there is a symbolic effect that may influence other countries to follow this "good" example. Hoel (1991) himself challenged the first argument, showing that unilateral action may influence the outcome of international environmental negotiations, inducing even higher total emissions. It is a standard result in the theory of public goods (Cornes and Sandler 1996) that unilateral abatement action would—at least to some degree—be offset by other countries' increases in emissions in response to the unilateral action (Vögele et al. 2019). However, this threat of carbon leakage[1] has not prevented the implementation of several unilateral abatement initiatives in recent years. This might be partly due to effects (e.g., information transmission and technological progress)[2] of unilateral action that could cause other countries to pursue stricter targets and counter carbon leakage (Arroyo-Currás et al. 2015). Behavioral influences are also among these effects, and Schwerhoff et al. (2018) stressed the importance of reciprocal behavior in this context.[3] This reciprocity aspect is consistent with the second argument presented above, implying that leaders wish to provide a good example.[4]

Reducing GHG emissions in economic sectors requires a complex set of policy measures, sometimes associated with the announcement of technology bans—which allows for a straightforward change in the power generation sector. Several studies have addressed the consequences of such unilateral technology-specific phaseout strategies on neighboring countries. Osorio et al. (2020) investigated the risks of Germany's plan to phase out coal-fired power plants in the context of the EU ETS. Matthes et al. (2019) emphasized that this may encourage fossil fuel-based electricity production in neighboring countries. De Menezes and Houllier (2015) and Bruninx et al. (2013) analyzed the effect of Germany's national policies to increase wind generation and phase out nuclear energy on the interconnected European power markets. De Menezes and Houllier (2015) showed that price shocks can be transferred between the regions, and the effect is constrained only by the available transmission capacity. The authors concluded that after the decommissioning of eight nuclear power plants in Germany in 2011, price volatility increased across EU markets, proving that the first mover can significantly affect interconnected regions. In the case of unilateral actions in the energy sector, these positive effects at national level are limited by the negative impact on the competitiveness of energy-intensive industries, e.g., analyzing consequences of unilateral action for Sweden by Sarasini (2009).

On the national level, first movers can stimulate competitiveness introducing technological innovation and setting standards—these advantages are highlighted by the *Porter hypothesis* (Porter and Van der Linde 1995). It stipulates that the enforcement of more ambitious environmental standards can be more advantageous than adapting to foreign

[1] Carbon leakage is defined as the additional CO_2 emissions of countries subject to a weak carbon policy compared to the CO_2 reduction achieved by pioneer regions with more ambitious policies.

[2] See, for example, Buchholz et al. (2019) and Eichenseer (2020) for such effects.

[3] Buchholz and Sandler (2016) included elements of behavioral economics in the standard model of public good provision and show that unilateral actions may then no longer be ineffective.

[4] Buchholz et al. (2014) investigated members of a subgroup of countries cooperating by reciprocally matching their public good contributions. In doing so, the subgroup takes a leader position in the game of public good provision.

technological and political conditions in the follow-up. However, the same argument can lead to a *technology lock-in*—e.g., deployment of CCSU projects that do not correspond to the future choice of capture technologies, transport capacity, or demand on gas composition (Stigson et al. 2012).

In contrast, in the present study, we consider a case where those taking unilateral action have a more ambivalent view of others' behavior. On the one hand, leaders would benefit from others following their action; from a climate protection point of view, any action is beneficial for all. On the other hand, other countries' delays in transitioning could mitigate the leader's transition costs. We particularly consider this second aspect of the ambivalent perspective of the ambitious country in this paper. We will see how these arguments are supported by the modeling framework and analysis of the total costs of the unilateral action—the transformation of the power sector under more stringent climate policy. To complete the analysis setting, we study the announced national energy and climate plans.

2.2 Review of national energy and climate plans for selected countries

The EC has established the rules and process of regular submission of NECPs for 2021–2030 (EC 2019b). These documents provide information on member states' national targets and their progress toward climate protection. The declared emission reduction targets in the ETS sectors are not binding in contrary to the EU wide emission reduction target of 43c % in 2030. The plans share a common structure that is designed to improve comparability and lead to better cross-border cooperation and efficiency gains. The member states' national plans describe their goals for energy efficiency, renewables, greenhouse gases, emission reductions, interconnections, and research and innovation. The EC aims to monitor the member states' progress toward these targets and to establish a legally binding framework (EC 2019a). Next, the EC "will take stock of the final plans and confirm whether they are consistent with the Union's 2030 targets or whether further efforts might be needed" (EC 2019a, 2). Having submitted their final NECPs in 2019, member states must provide progress reports every two years (EC 2018a).

Although the EU strives for a higher level of market integration with unified regulations, our analysis of the published reports shows that national energy markets and regulatory frameworks present different levels of ambition to achieve the 2030 emission reduction targets. Differences arise from several factors: (i) national emission reduction targets, (ii) promotional measures or bans, and (iii) renewable energy targets.

Decarbonization strategies, and particularly sector-level emission reduction targets, are a major part of every NECP. Under dimension (I), *decarbonization*, the collective GHG reduction targets are reported for both the sectors inside the EU emission trading system (ETS) and non-ETS sectors. Among the ETS sectors, power generation represents a significant share of greenhouse gas emissions and, consequently, significant potential savings: in 2019, the sector accounted for 62% of overall ETS CO_2 emissions[5] (EEA 2020a). In the discussion below, we will focus on the specific aspects that drive the divergence of national policies.

[5] Item "combustion of fuels" refers to the sum of all stationary installations' emissions, in the scope of ETS Phase 3. Combustion of fuels includes mainly electricity generation plus various manufacturing industries, for a detailed description of activities and sectors covered, see EEA data viewer Background Note.

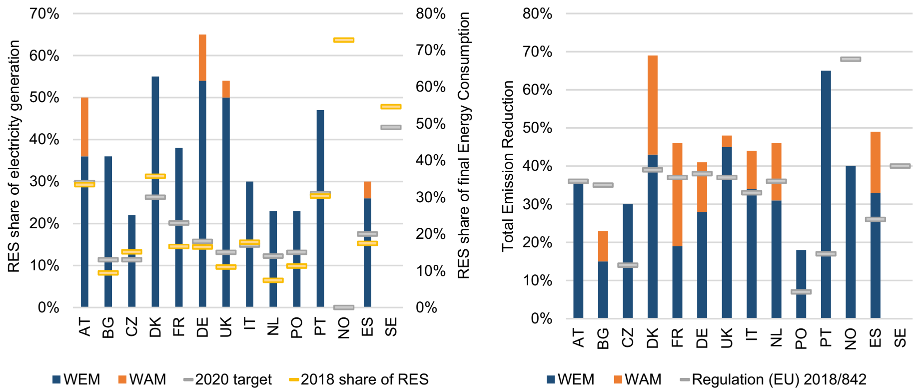


Fig. 1 National RES development in 2020 (**a**) and 2030 emission reduction targets in sectors covered by Effort Sharing Regulation (2018/842) (**b**). Sources: own compilation, based on (EC 2009, 2019b, 2018a, Eurostat 2019). Note: for Norway and Sweden, the data was not reported at the time when drafts of NECPs were evaluated

2.2.1 Emission reduction targets

If met, the EU's collective emission reduction targets formulated in the 2030 Climate and Energy Framework would reduce emissions by 40% by 2030 compared to 1990 levels. Sectors included in the EU ETS are subject to a 43% cut. A single EU-wide cap that introduces centralized EU-wide allocation of allowances has replaced individual national caps starting with the third phase of the EU ETS. Non-ETS sectors[6] needed to reduce emissions by 30% (compared to 2005 levels) with targets introduced at the national level (2018a). The current progress of renewable energy share in power generation in 2020 in some countries has progressed significantly more than the previous 2020 target (see Fig. 1). Although emissions covered by the Effort Sharing Regulation (ESR 2018/842) remain challenging and cover all non-ETS emissions, our analysis is focused on the emission reduction targets for the energy sector; see Table 1, column "Reduction below 2005 levels (energy)."

2.2.2 Technology-specific bans

Several EU member states have implemented technology-specific bans. The nuclear accident of Fukushima caused an extensive public and political discussion on the future of nuclear power in Europe. In Germany, this discussion resulted in a planned phaseout of nuclear energy by 2022. However, the reaction to this incident varied across EU member states. While Germany declared a moratorium on nuclear power stations, the UK stood by its decision to expand its nuclear power capacity. As of 2019, 14 member states have nuclear reactors (IAEA 2020a). Of those 14 states, four plan to phase out nuclear power or to block the construction of new reactors. A similarly fractured picture emerges in the case of coal-fired power plants. Nine member states announced a complete phaseout of

[6] The sectors not included in the EU ETS, however, are subject to individual national obligations. Those cuts are regulated by the Effort Sharing legislation and are based on the respective Member State's relative wealth.

Table 1 Overview of national policy goals and objectives set on EU level

State	Bans [or: max. share in el. generation]	Year	RES share total (and in electricity gen.)		Carbon budgets (energy[2])	Reduction below 2005 levels (energy[2])	
			WEM[1]	WAM		WEM	WAM
			2030	2030	2005	2030	2030
			[%]	[%]	[$MtCO_2e$]	[%]	[%]
Austria	Coal[4]	2020	36 (23)	46–50 (100)	16.3	−60	
Belgium	Nuclear	2035	36		29.4	+2	+5[5]
Czech Rep.	Coal	2033	22 (17)		63.2	−33	
Denmark	Coal	2030	55 (109)		23.2	−43	−47
France	Coal	2022	38 (40)		66.7	−10	−40
	Nuclear [50%]	2035					
Germany	Nuclear	2023	54 (53)	65 (62)	379.4	−34	−54
	Coal	2038					
Great Britain	Coal	2024	(50)	(54)	214.4	−68	
Italy	Coal	2025	30		159.1	−49	−65
Netherlands	Coal	2030	23		68.2	−73	−79
Poland	Coal [60%]	2030	23 (32)		178.5	−16	
Portugal	Coal	2030	47		25.5	−93	−95
Norway	–		–			−12	
Spain	Coal	2030	26	30	126.6	−62	−82
	Nuclear	2040					
Sweden	Coal	2022			10.8	−33	
	Nuclear	2040					

[1]WEM stands for developments with existing measures and WAM for more ambitious targets with additional measures

[2]Reductions are given for IPCC sector Energy 1.A.1 and estimated with the base of 2005 where necessary; some countries reported reductions with a base of 1990 (EEA 2020b)

[3]Total (without LULUCF and aviation), non-binding, estimated based on the given NECP emission reductions under WEM and WAM

[4]Hard coal and lignite if given. Other European countries that announced a coal phaseout after the analysis was completed: Bulgaria (2040), Croatia (2033), Ireland (2025), Slovenia (2033), Slovakia (2030)

[5]For Belgium, total greenhouse gas emissions (excluding LULUCF) are expected to increase between 2015 and 2030, expected mainly due to an increase in emissions from newly installed gas-fired power generation substituting for the nuclear power fleet due to phaseout by 2025

Sources: (EC 2019b, 2018a, 2009)

coal-fired power plants, while in several countries with a historically significant share of coal in their electricity mix (e.g., Germany), a coal phaseout became part of the political discussion. In the context of the European Green Deal, the question may arise whether intervention in the form of a ban on coal-fired power generation is necessary. Pietzcker et al. (2021) show that coal might be almost entirely phased out by 2030. Phasing out coal-fired power plants is usually linked to concerns about climate change. In terms of climate protection, an alternative approach to a complete phaseout is the deployment of carbon capture and storage (CCS) or carbon capture and utilization (CCU) technologies. However, the implementation of CCS has proved to be complicated. In many cases, it is accompanied by a high level of public opposition; see, e.g., Vögele et al. (2018) and Upham and Roberts (2011). Table 1 provides an overview of the status of the national phaseout plans and technology-specific bans of individual EU member states as well as renewable energy expansion targets and planned greenhouse gas (GHG) emission reductions. The NECPs contain estimates for baseline developments *with existing measures* (WEM) and for more ambitious targets *with additional measures* (WAM).

2.2.3 Renewable energy targets

A similar fractured picture emerges when considering expansion targets for renewable energies. The Renewable Energy Directive (EC 2009) stipulated that renewable energy should cover 20% of gross final energy consumption by 2020. Individual targets were set for the respective member states, taking into account the starting point of renewable capacities and the national potential for energy production from renewable sources. In 2018, a revised Renewable Energy Directive (EC 2018c) entered into force. This directive raised the target for renewable energy share to 32% of final energy consumption by 2030. However, this updated version does not set country-specific minimum limits for 2030. Instead, the targets for 2020 are considered minimum contributions to the new 2030 framework, while the EU-level target is intended to give member states flexibility to "meet their greenhouse gas reduction targets in the most cost-effective manner in accordance with their specific circumstances, energy mix and capacity to produce renewable energy" (EC 2018c, 83). Figure 1 shows the national targets for RES deployment (left) and emission reduction (right) as stated in the respective NECPs in comparison to (EC 2009) and (EC 2018b).

2.2.4 Summary

The national targets for emission reductions and expansion paths for renewable energies differ considerably. As the examples above show, the current system of national energy policies across member states is fractured. Individual targets and national political orientation significantly affect the structure of regional electricity markets. Despite the EU's efforts, frequent revisions of voluntary targets for 2020 reported in NECPs pose challenges in evaluating and ensuring transparent progress toward achieving energy reduction goals at both national and EU levels, necessitating careful monitoring and coordination among participating countries. The increasing integration of European electricity markets introduces a complex dynamic, wherein de Menezes and Houllier (2015) illustrate the potential transmission of price shocks between different regions across Europe.

3 Analysis

3.1 Analysis setting

Contributing to climate change mitigation can be regarded as providing a global public good. Consequently, the incentive to freeride will impair mitigation contributions from the perspective of individual countries, leading to sub-provision. As described above, countries' targets regarding emission reduction and the development of RES capacities across EU member states vary strongly. Therefore, the question arises as to why some member states commit themselves to ambitious emission reductions and what effects this decision that has on a highly interconnected electricity system.

This analysis will focus on the national power sector policies of Germany, France, and their neighboring countries. The selection of these markets is based on two dimensions: (i) their relative significance within the European electricity markets and (ii) the divergence of national energy policy between them. The French and German markets rank the highest in terms of overall electricity generation, and together they accounted for 47.4% in 2019 of gross electricity generation within the EU (Eurostat 2019). Due to Germany's geographical location, its electricity market is highly interconnected with neighboring markets. Furthermore, in the context of the *Energiewende*, Germany strives for ambitious targets regarding the development of renewable energy capacities. At the same time, it is pursuing a complete phaseout of nuclear power generation.

Contrary to its determined emission reduction targets, a nuclear phaseout could increase the need for fossil-fueled balancing capacities (see, e.g., Bruninx et al. 2013 and Knopf et al. 2014). However, coal-fired generation will also be phased out and will be eliminated no later than the end of 2038 under the Act to Reduce and End Coal-Fired Power Generation (KVBG 2020). This limits balancing options and demands the further transformation of the German power sector. In France, on the other hand, a significant share of electricity is provided by nuclear reactors. As of 2018, 71.6% of electricity was supplied by nuclear power plants (IAEA 2020b). However, France plans to cut its reliance on nuclear power to 50% by 2035. Given this fractured regulatory and policy framework, we aim to evaluate potential distorting effects on electricity markets by applying a bottom-up linear optimization model of the European electricity market. We further develop the approach of combining electricity market modeling with game-theoretic considerations as presented in Weissbart (2020), where a bottom-up European electricity market model was used in a cooperative game setting to analyze the total system costs of regions coordinating to maximize welfare under their respective climate goals.

3.2 Model description

Box: Nomenclature

cb_d	Carbon budget of a country d	[t CO_2]
$Cst^{var}_{i,d}$	Variable generation costs	[€/MWh]
$Cst^{fix}_{i,d}$	Quasi-fixed annual costs (e.g., labor costs)	[€/MW]
$Cst^{inv}_{i,d}$	Investment costs (annuity recalculated from overnight costs)	[€/MWe]
$D_{h,d}$	Hourly electricity demand	[MWh]
d, k	Set of countries (alias)	[–]
e_i	Emission coefficient for each technology i	[t $C0_2$/MWh]
$ef_{i,d}$	Specific efficiency factor for each technology i	[–]
$G_{h,i,d}$	Total available generation capacity in the period	[MW]
$G^{inst}_{h,r,d}$	Installed generation capacity at the beginning of the period of dispatchable generation (coal, gas, nuclear, etc.)	[MW]
$G^{inst}_{h,v,d}$	Installed generation capacity at the beginning of the period of variable generation types (wind on- and off-shore, PV)	[MW]
$G^{inv}_{h,r,d}$	Invested generation capacity (coal, gas, nuclear, etc.)	[MW]

Box: Nomenclature

$G^{inv}_{h,v,d}$	Invested generation capacity (wind on- and off-shore, PV)	
$G_{h,i,d}$	Total generation capacity	[MW]
h	Specific hour of the year	[–]
$I_{h,k,d}$	Electricity imports from country k to d and $I_{h,d,k}$ electricity exports from d to k	[MWh]
i	Electricity generation technology index	[–]
$Pr_{h,i,d}$	Electricity production	[MWh]
$p^{ex}_{h,d,k}$	Regional market-clearing prices in the exporting region, importing region—$p^{im}_{h,d,k}$	[€/MWh]
tc_d	Total system costs of country d	[€]
$\alpha_{h,i,d}$	Technological availability factors for dispatchable technologies i	[–]
$\varphi_{h,v,d}$	Exogenous generation profiles for variable technologies r	[–]

Our partial-equilibrium bottom-up model EMME[7] features the EU27 plus UK, including Norway and Switzerland. We endogenously modeled electricity dispatch and investment in generation capacities by minimizing total system costs. The model was calibrated to the base year 2015. Total system costs consist of overall variable generation costs and investment costs. The electricity production is subject to the available generation capacity (Eq. (2)). In the model, the demand is an exogenous input and is given as a price-inelastic time series in hourly intervals.

$$\min \mathrm{Cost} = \sum_{h,i,d} \left[\mathrm{Pr}_{h,i,d} \bullet Cst^{var}_{i,d} \right] + \sum_{i,d} \left(G^{inv}_{i,d} \bullet Cst^{inv}_{i,d} \right) \tag{1}$$

$$\mathrm{Pr}_{h,i,d} \leq G_{h,i,d} \quad \forall h, i, d \tag{2}$$

Equation (3) describes the energy balance constraint.

$$\textstyle\sum_i \mathrm{Pr}_{h,i,d} + \sum_k I_{h,k,d} - \sum_k I_{h,d,k} = D_{h,d} \quad \forall h, d \tag{3}$$

The existing cross-border net transfer capacity restricts electricity transfers between two nodes:

$$I_{h,k,d} \leq NTC_{k,d};\ I_{h,d,k} \leq NTC_{d,k} \quad \forall h, d, k \tag{4}$$

Variable renewable generation is determined via exogenous generation profiles, described in Eq. (5), while the actual availability of dispatchable generation technologies is determined by Eq. (6). Equation (7) sums up of all available capacities per hour and country, including installed and invested capacities at the beginning of the year:

$$G_{h,v,d} = \left(G^{inst}_{h,v,d} + G^{inv}_{h,v,d} \right) \bullet \varphi_{h,v,d} \quad \forall h, v, d \tag{5}$$

$$G_{h,r,d} \leq \left(G^{inst}_{h,r,d} + G^{inv}_{h,r,d} \right) \bullet \alpha_{h,r,d} \quad \forall h, r, d \tag{6}$$

$$G_{h,i,d} = G_{h,v,d} + G_{h,r,d} \tag{7}$$

[7] A more detailed description of the model is provided in (Govorukha et al. 2020).

Table 2 Combinations of leading (WAM) and lagging countries (WEM)

Member state	Scenarios							
	c_0	c_de	c_fr	c_1	c_2	c_3	c_4	c_n
	–	DE	FR	DE, FR	Other	Other & DE	Other & FR	All
France WAM			x	x			x	x
Germany WAM		x		x		x		x
Other* WAM					x	x	x	x
If no cross then	WEM	WEM	WEM	WEM	WEM	WEM	WEM	WEM

*Other countries, as given in Table 1, except for DE and FR

Equation (8) sets a cap on the emissions from electricity generation in each country d, where cb_d is a carbon budget for the respective modeled year. This cap sets a total amount of emissions that can be emitted by new and existing power plants, affecting the choice of capacity additions and operation of the installed capacities.

$$\sum_{h,r,i}\left(\frac{e_i}{ef_{i,d}} \bullet \mathrm{Pr}_{h,i,d}\right) = cb_d \;\; \forall d \tag{8}$$

To facilitate the modeling and decrease solution time, we used simulated representative wind, solar, and load time series for each country generated with the *tsam* algorithm presented in (Kotzur et al. 2018).

As described in the previous section, decarbonization commitments and RES expansion targets vary significantly across member states. Table 1 compares the national goals described in the NECPs to the objectives defined in EU regulations. Some member states aim for a reduction in overall carbon emissions that exceeds the jointly adopted EU targets (e.g., Denmark, United Kingdom, Portugal) already in the WEM scenarios (Table 1). In contrast, others show that the common emission reduction targets will be challenging to achieve, and additional measures will be necessary. Moreover, some countries have introduced technology-specific bans and phaseout plans that could further aggravate the situation.

We implement the NECPs' targeted emission abatements as national carbon budgets by relating the percentage reduction to the emission levels of 2005, shown in the column "Carbon budgets (energy)" in Table 1. Due to the electricity market's structure, we adopt national RES targets as indicative benchmarks rather than explicit capacity constraints without necessarily aiming to achieve the Member State RES capacity expansion targets.

Both WEM and WAM estimations were implemented in the model design. In order to assess the implications of individual precursors, this study compares the possible effects of single countries' pursuit of ambitious energy and climate policy goals with a situation in which either all member states (represented by WAM estimations) or none (represented by WEM estimations) adhere to more stringent goals. As described above, this study focuses on the electricity markets of Germany, France, and their neighboring countries. Hence, we considered the combinations in Table 2. We set up the analysis as a one-shot game. This is mainly driven by the setting of our experiment that focuses on benefits of forerunner that chooses WAM, while assuming others to play WEM. In a sequential game, the players deciding first observe the subsequent stages and then choose (at the first decision node) the strategy that is beneficial for them (anticipating the later decisions of the others). This behavior however does not represent the aim of our experiment setting.

The modeling framework allows individual countries to invest in all available generation technologies unless there are explicitly formulated political goals for the phaseout of individual technologies (as described in Table 1). In countries where there is a partial ban that limits only a certain share of coal and nuclear-based generation in the national generation mix (e.g., France and Poland), investments are limited to the respective level.

4 Results and discussion

In the following sections, we discuss the main findings and conclusions from the analysis, addressing changes in the individual countries' payoffs, wholesale market prices, transfers between the modeled countries, and investment in new generation capacities.

4.1 Analysis of individual payoffs

We implemented the targeted national carbon budgets from the NECPs and calibrated the model to the year 2015 so that the emissions from power sector reflect the historic emissions. The analysis assumes that countries have the choice between the two development paths referred to in the NECPs as WEM and WAM and that they consider other member states' strategies when choosing between the paths.

Each player's total system costs tc_d are defined as the country's d total expenses for the provision of electricity. Each country seeks to minimize those expenses. tc_d are composed of variable generation costs $Cst_{i,d}^{var}$, investments in new generation capacities, and the value of net exports $\sum_k I_{h,k,d} \bullet p_{h,d,k}^{im} - \sum_k I_{h,d,k} \bullet p_{h,k,d}^{ex}$. Investment costs are calculated as the total quantity of newly built generation capacity $G_{i,d}^{inv}$ (measured in MW) multiplied by the investment costs $Cst_{i,d}^{inv}$ (measured as annuity payment in $\frac{\mathrm{EUR}}{\mathrm{MW}}$) of the generation technology i installed within the modeling horizon. The value of interregional trade is defined as the difference of electricity imports $I_{h,k,d}$ and exports $I_{h,d,k}$ multiplied by the regional market-clearing prices in the exporting $p_{h,d,k}^{ex}$ and importing $p_{h,d,k}^{im}$ regions, respectively. These prices are derived from the shadow prices of the regional market-clearing constraints. The total regional expenses are calculated as follows:

$$\mathrm{tc}_d = \sum_{h,i,d} \left[\mathrm{Pr}_{h,i,d} \bullet Cst_{i,d}^{var} \right] + \sum_{i,d} \left(G_{i,d}^{inv} \bullet Cst_{i,d}^{inv} \right) + \left(\sum_k I_{h,k,d} \bullet p_{h,d,k}^{im} - \sum_k I_{h,d,k} \bullet p_{h,k,d}^{ex} \right) \quad \forall d \tag{9}$$

By comparing different cases in which Germany, France, and the neighboring countries pursue more (WAM) or less ambitious (WEM) energy and climate policy goals, we can determine the effects on the total national expenses of a state (Table 3).

Figure 2 provides an overview of the total expenses of Germany, France, and the neighboring countries (as described in Eq. (8)) in relation to the decision of the respective other actors.

Aiming for a more ambitious reduction in carbon budgets is the more advantageous strategy in all combinations (Fig. 2). However, the expenses depend on neighboring countries. If other countries delay their advanced policies, a forerunner can potentially reach their WAM targets at lower costs. This can be illustrated by the case of Germany. When other member states choose WAM (Fig. 2a), Germany's expenses are the lowest if France

Table 3 Differences in the value of total expenses across countries and scenarios (billion euros)

	c_0	c_de	Δ to c_0	c_fr	Δ to c_0	c_1	Δ to c_0	c_2	Δ to c_0	c_3	Δ to c_0	c_4	Δ to c_0	c_n	Δ to c_0
DE	15.15	10.43	−31%	16.19	7%	10.48	−31%	17.10	13%	10.71	−29%	17.85	18%	10.76	−29%
FR	12.22	13.81	13%	11.48	−6%	12.78	5%	13.82	13%	14.77	21%	12.75	4%	13.40	10%
Other	66.24	71.69	8%	66.38	0%	73.15	10%	63.47	−4%	71.19	7%	64.24	−3%	72.93	10%
Sum	93.61	95.93	2%	94.05	0%	96.41	3%	94.39	1%	96.67	3%	94.85	1%	97.09	4%

		DE	
		WAM	WEM
FR	WAM	- 10,76 - 13,40	- 17,85 - 12,75
	WEM	- 10,71 - 14,77	- 17,10 - 13,82

(a) Other WAM

		DE	
		WAM	WEM
Other	WAM	- 10,76 - 72,93	- 17,85 - 64,24
	WEM	- 10,48 - 73,15	- 16,19 - 66,38

(c) FR WAM

		FR	
		WAM	WEM
Other	WAM	- 13,40 - 72.93	- 14,77 - 71,19
	WEM	- 12,78 - 73,15	- 13,81 - 71,69

(e) DE WAM

		DE	
		WAM	WEM
FR	WAM	- 10,48 - 12,78	- 16,19 - 11,48 -
	WEM	- 10,43 - 13,81	- 15,15 - 12,22

(b) Other WEM

		DE	
		WAM	WEM
Other	WAM	- 10,71 - 71,19	- 17,10 - 63,47
	WEM	- 10,43 - 71,69	- 15,15 - 66,24

(d) FR WEM

		FR	
		WAM	WEM
Other	WAM	- 12,75 - 64,24	- 13,82 - 63,47
	WEM	- 11,48 - 66,38	- 12,22 - 66,24

(f) DE WEM

Fig. 2 Payoff matrixes (billion euros) [Given the payoffs in the matrices, WAM is the dominant strategy in a one-shot game; players will deviate from WEM and will choose WAM regardless of what the other player(s) do(es). It will not make a difference to play this game sequentially (given the displayed payoffs): players will always choose WAM, regardless of what others do at earlier or later stages of the game, preferring others to play WEM.]

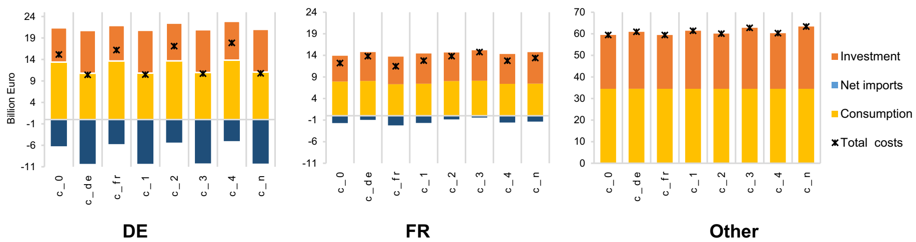


Fig. 3 Decomposition of total costs in a million EUR [The total expenses shown in Fig. 3 represent the results of the cost optimization and does include the shadow price for CO_2 emissions. A discussion on the marginal abatement costs is provided in Section 4.3]

lags behind. Germany's costs are approximately EUR 53 million lower than when France chooses WAM as well. Similarly, if France and other member states only enforce existing measures, it is advantageous for Germany to choose WAM (see Fig. 2b). In this case, Germany's expenses decrease by EUR 56 million. In our model, if Germany alone pursues more ambitious climate goals (Fig. 2b, lower left quadrant), it saves EUR 335 million compared to the situation in which everyone chooses WAM (Fig. 2a, upper left quadrant). Hence, when fewer countries also follow the WAM strategy, Germany can spend less to achieve WAM goals. In general, the same conclusion is correct for France and the remaining member states as well.

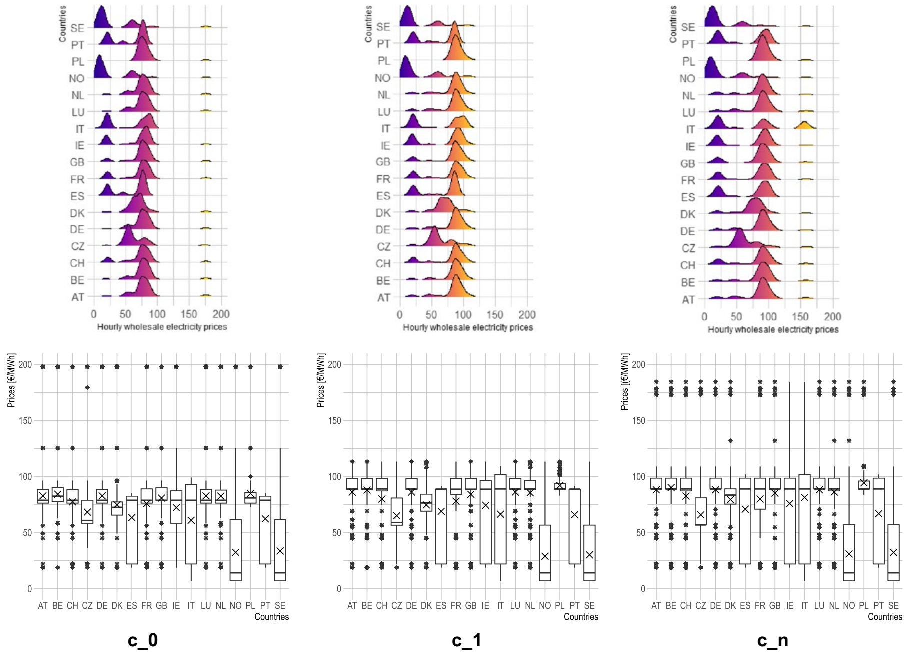
Yet, an examination of total expenses shows that the configuration in which all countries select WEM represents the most favorable alternative overall (Table 3). From an individual player's perspective, however, it is always beneficial to unilaterally deviate from that strategy. It is more beneficial to adopt the WAM strategy if others choose WEM; this can be seen if we compare the total expenses for choosing WAM between the upper row of Fig. 2 (a, c, e) and the lower row (b, d, f).

The results show that forerunners have an incentive to push ahead with the transformation of their own electricity sector while other countries lag behind. Moreover, it is disadvantageous for forerunners if other countries pursue ambitious climate goals at the same time. At first glance, this result appears counterintuitive since a transformation of the power sector toward a low carbon system is associated with high costs. This finding can be explained by investigating Fig. 3, which provides a breakdown of the total national expenses for electricity provision, regarding investments, consumption, and export revenues. The results indicate that a country's decision regarding WEM or WAM impacts the overall investments. The constraint of lower carbon budgets under WAM results in more investments in additional generation capacities. Yet, the replacement of capacities that are beyond their lifetime and already existing technology-specific bans also shape the pattern of future investments both in WEM and WAM scenarios.

In Germany, the overall sum of investments in new capacity hardly reacts to the climate strategy of neighboring countries. This can be seen by comparing overall investments in the configurations *c_de*, *c_1*, *c_3*, and *c_n* with the configurations *c_0*, *c_fr*, *c_2*, and *c_4*. A similar picture emerges when considering variable generation costs. Both variables appear to be driven mainly by Germany's own energy and climate policies. Generally, a stronger focus on investments in RES in WAM decreases marginal generation costs, which brings expenses for electricity consumption down. An analysis of electricity trade shows that Germany can produce considerable revenues from exporting electricity, especially if it follows a more ambitious climate policy under WAM. When renewable energy sources are abundant in Germany, fossil fuel power plants in neighboring countries are forced out of the market due to the merit order effect. In the context of electricity prices, margins from renewable energy exports increase when the importing countries themselves have a higher share of fossil fuel generation capacities. On the other hand, Germany only relies on imports for balancing purposes for a few hours a year.

Thus, our results indicate that if one country proceeds on its own, neighboring countries may indirectly share the costs of decarbonization. The effects of increasing the share of variable renewable generation are the focus of many studies (see, e.g., Hirth and Ueckerdt 2013). Researchers have paid particular attention to the fact that negative spot market prices have appeared more regularly since Germany deployed more renewable energy sources. The occurrence of negative prices as a result of the expansion of renewable energies may appear to contradict the findings above. However, negative prices remain the exception rather than the norm. In 2019, negative prices occurred for 211 h. This corresponds to approximately 2.5% of the trading period of that year (BNA 2019). Moreover, Germany generates substantial revenues from exporting electricity; in 2019, together with the dramatic increase in wind capacity, net electricity exports amounted to about EUR 1.2 billion (Fraunhofer ISE 2020). Moreover, there is no clear evidence that average export prices were lower than import prices. Therefore, the results are congruent with the lessons of the past, at least for medium-term developments up to the year 2030. If Germany implements additional measures, the revenues from exports will rise considerably (Fig. 3). The difference between *c_0* and *c_de* is explained by an interplay of increased investment costs compensated by revenues from net exports: more power is sold to neighboring countries. Additionally, there is a decrease in the expenses on inland electricity production, which itself is caused by changes in the pattern of interregional trade.

It is essential to add that we do not assume support mechanisms for wind and solar. In the case of offshore wind, there is already strong evidence of the technological competitiveness of the projects coming into operation in 2021–2023 (Jansen et al. 2020). In our model, wind and solar investments are pushed by stricter carbon budgets, which raises the endogenous cost of emissions, defined as a shadow price of the carbon budget constraint (e.g., in *c_de* for Germany, it is roughly EUR 76 per ton of CO_2 in 2030).



Note to the boxplot: x – annual average price, single dots – are outliers.

Fig. 4 Wholesale electricity prices (€/MWh) in 2030

It is often argued that forerunners in climate policy can encourage other players to join climate change mitigation actions and treaties. We show that a different picture emerges from the consideration of strategic decision-making. If no binding uniform framework exists, the two aspects discussed below could be of more importance than a mere "role model" function of the pioneer.

This section examined the rationale for unilateral action and found two key trends: (1) the "race to the top," in which the decarbonization of one market can be partially carried out on the shoulders of neighboring markets if they do not themselves implement more stringent measures at the same pace, and (2) when more countries take a more ambitious path, the cost of implementing more ambitious targets rises for all actors.

4.2 Wholesale market prices

In this section, changes in wholesale electricity prices are related to the results of the total system costs determined in the previous chapter. Tighter carbon budgets for the power sector increase the mean values of electricity prices; compare the box plots for scenarios *c_0* and *c_n* in Fig. 4, where means are marked as crosses. Price means for most countries tend to be higher in the scenario where each country follows the WAM strategy, with higher variance and more persistent occurrence of hours with high prices across the interconnected regions. Table 4 of the Appendix shows the variances of wholesale prices between the scenarios. If only Germany and France strive for more advanced policies, the average prices in the neighboring countries increase along with the prices' variance. This effect is

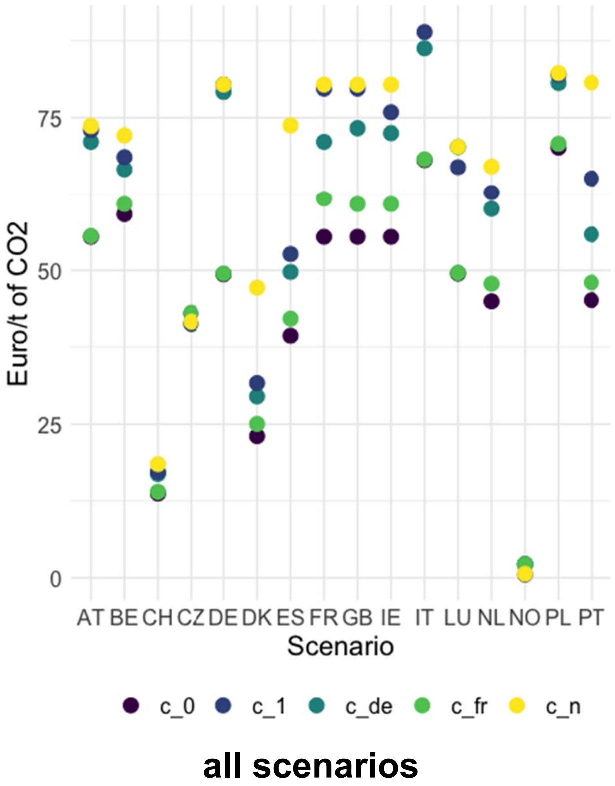


Fig. 5 Marginal abatement costs in 2030

only limited by the available interconnection capacities between neighbors, with Germany retaining the position of a net exporter. The increase in price variance can be explained by the investments in the *c_1* scenario, which increase the expansion of photovoltaics and wind. France continues to invest in nuclear power, but decommissioned nuclear capacities are being replaced by both new nuclear power plants and renewable energy facilities, gradually reducing the total nuclear fleet. These developments in the generation mix shift more expensive (in terms of variable costs) gas and coal-fired capacity to the right side of the merit order. The increase of variable renewables in the mix for most hours of the year increases the price volatility, which is transferred to the interconnected regions. These findings are consistent with the arguments of de Menezes and Houllier (2015) that price shocks can be transferred between regions. Another notable effect is that hours with high price peaks in neighboring countries are reduced in the WEM scenario. As the density plots in Fig. 4 show, the prices for most hours of the c_1 scenario are distributed more densely in the range of middle and high prices. Additional information about changes in the variance in wholesale electricity prices can be found in the Appendix, Table 4.

It is important to note that in the current formulation of the model, wholesale prices are influenced by the constraints imposed on the national carbon budgets (Fig. 5). This places additional endogenous costs on emissions from fossil fuel electricity generation. Therefore, the prices reflect both the variable costs of electricity generation and the costs of more stringent policy targets for emissions in the electricity sector.

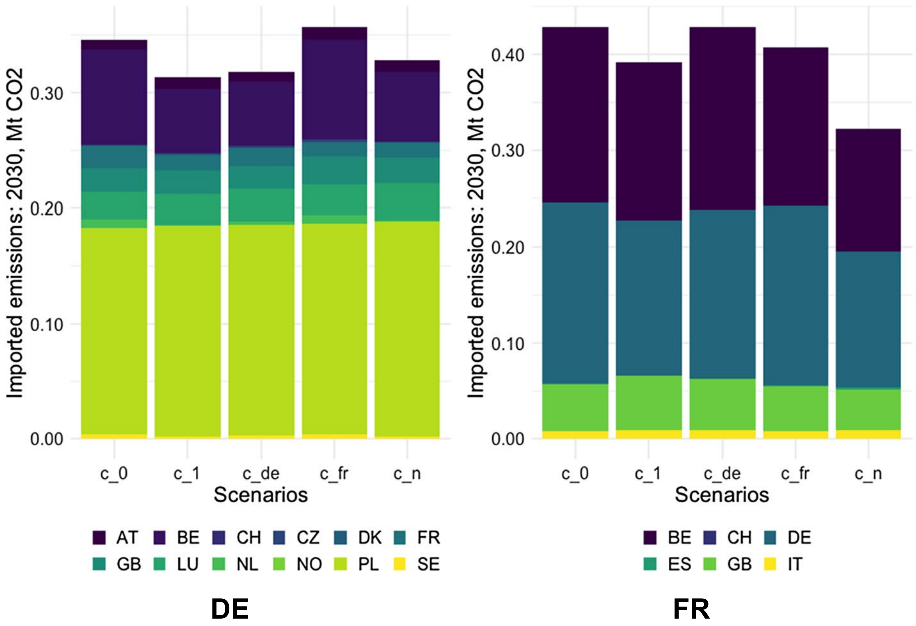


Fig. 6 Imported emissions in 2030

4.3 CO_2 emissions

As noted in the previous section, the constraint imposed on the national carbon budgets in Eq. (8) creates an endogenous shadow price on the emissions of fossil fuel electricity production. The shadow prices can be interpreted as marginal abatement costs for the power sector in the respective region. Figure 5 shows the marginal abatement costs for all scenarios and member states in the modeling scope. The data behind the figure can be found in the Appendix, Table 6. They are compatible with the prices found in recent scientific studies and sector-specific publications (Osorio et al. 2020, ENTSO-E 2019). As expected, the scenario *c_0* shows lower regional marginal abatement costs for most countries. On the other hand, the scenario *c_n*, which has the highest total reduction of CO_2 emissions in the electricity sector, shows the highest shadow prices among all scenarios.

Figure 6 shows the estimated imported emissions as a total volume of imports multiplied by the emission intensity of total electricity generation in the exporting country during the import period. Most of Germany's imported emissions come from Poland's fossil-fueled generation capacity, and this share remains relatively stable across the scenarios. The higher share of emissions imported from Belgium can be explained by the country's national strategy of expanding gas-fired capacity in the face of the nuclear phaseout in 2025. Interestingly, the value of imported emissions for Germany in *c_fr* is comparable to *c_0*. Similar to the Belgian case, this can be explained by the French reduction of nuclear generation capacity and expansion of gas-fired generation.

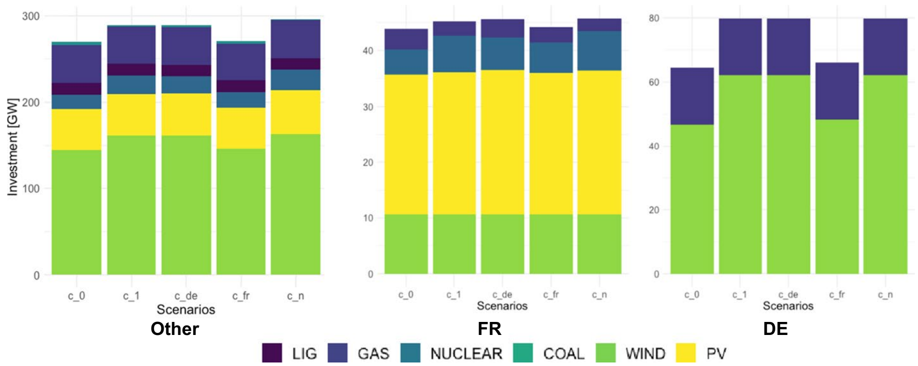


Fig. 7 Investment [MW]

4.4 Investment

Scenario *c_n*, with additional extended measures that tighten carbon budgets for the power sector, causes more investments in renewable capacity, and in particular wind and PV, across the selected European countries (Fig. 7). Consequently, the total expansion of generation capacities is also the highest in scenario *c_n*. Interestingly, the tightening of the German carbon budget alone has a comparably strong effect on the overall investment of other countries, with France having only a limited impact in *c_fr*. This can be explained by the substantial expansion of interconnection capacity envisaged in the Entso-E TYNDP of 35.5 GW net transmission export capacity from Germany in 2030, which is the largest planned expansion volume among the European countries discussed here. Further information about the investment costs and technology choices applied in the model can be found in the Appendix, Tables 5 and 6.

5 Concluding remarks and discussion

In this study, we implemented a linear optimization model of the European electricity market to find a partial-equilibrium solution for different policy regimes. The model produced valuable and comprehensible results on regional investments, the development of wholesale electricity prices, and endogenous marginal abatement costs. Some limitations of the model stem from simplifications made to gain tractability, and these limitations must be considered with caution when interpreting the results. The limitations include the scope of modeled technological options, assumption of exogenous ETS price without considering ETS reform, and operation of the Market Stability Reserve. The total system costs alone are not a sufficient indicator of the different transition paths of the power sector because they can be rigid to structural changes. Therefore, an analysis of the marginal abatement costs, investment patterns, and imported emissions was applied to fill this gap.

The present analysis addresses only the European power sector, neglecting the other sectors of the EU ETS (combustion of fuels in the energy intensive industry for energy and non-energy uses). It would be worthwhile to carry out a similar analysis including these sectors and the new support mechanisms that will come into force with Phase IV of the ETS in 2021 to counter the risk of carbon leakage.

NECPs provide new and valuable insights into the current and upcoming changes in the energy sectors of EU member states. The analysis is based on the NECPs and focuses on the progress and national commitments to reduce CO_2 emissions in the electricity sector.

As outlined in the introduction, this study aimed to analyze the possible motives for ambitious emission reduction goals and technology-specific phaseouts in selected European countries. Eight scenario groups were analyzed, highlighting the ambitious unilateral action of either Germany, France, or their simultaneous commitment to advanced emission reduction targets and transformation of the power generation sector. Additional scenarios helped to show changes in neighboring countries and their interest in pursuing more or less ambitious emission reduction policies. The analysis of the total cost of operating and transforming the national electricity sectors revealed two main trends that explain the pursuit of ambitious unilateral commitment: (1) the costs of early action can be redistributed to a certain extent to neighboring markets that do not have the ambition to pursue more ambitious emission reductions and transformation of the power sector; and (2) the total costs spent by all member states increase as more countries accede to advanced policy regimes. On the national level, the effect of these two trends is considerably determined by the role (net exporter or net importer) of the country in the European electricity market, its interconnection capacity, and the structure of its generation mix.

We acknowledge that ETS has undergone significant reforms, including the introduction of the Market Stability Reserve (MSR) and updates to the National Climate and Energy Plan (NECP). The MSR aims to address the surplus of allowances in the market and improve the system's resilience to future shocks, while the updated NECP sets more ambitious targets for greenhouse gas emission reduction. These developments have potentially affected the benefits for frontrunners and the cost assumptions in our study. The stricter targets and the MSR mechanism may lead to increased pressure on frontrunners to reduce emissions, resulting in higher costs and a shift in the competitive landscape. However, our paper offers valuable insights into the historical context and policies in place at the time of our research, which remain relevant for understanding the evolution of the field and informing future policy design and decision-making.

Appendix

Table 4 Variance in wholesale electricity prices

		DE	FR	GB	NL	BE	DK	SE	LU	PL	CZ	AT	CH	IT	ES	NO	IE	PT
2030	c_0	470	431	595	426	441	442	125	47	303	514	470	755	951	613	130	102	639
2030	c_1	566	105	794	553	493	516	120	566	219	588	566	923	1331	846	125	131	895
2030	c_de	548	102	758	538	474	509	122	548	223	580	548	909	1307	836	127	126	884
2030	c_fr	482	631	603	440	450	449	124	482	294	526	482	772	983	639	1290	104	667
2030	c_n	738	130	954	779	661	719	140	738	259	653	738	1117	2742	1162	142	150	1284

Table 5 Investment cost assumptions behind the scenarios

	Lifetime [Years]	Overnight costs* [2015 EUR/kW] 2020	O&M annual costs [2015 EUR/kW] 2020	Overnight costs [2015 EUR/kW] 2025	Overnight costs [2015 EUR/kW] 2030
Nuclear	40	5580.0	148.7	5468.4	5301.0
Coal (conventional)	30	1209.0	40.56	1209.0	1209.0
Coals (CCS)	30	2.4400	171.2	2440.3	2440.3
Lignite (conventional)	30	1395.0	40.5	1395.0	1395.0
Lignite (CCS)	30	2626.0	171.2	2626.3	2626.32
Gas (CCGT)	30	744.0	22.5	744.0	744.0
Gas (OCGT)	30	37.0	18.0	372.0	372.0
GAS (CCGT +CCS)	30	1271.0	90.1	1271.3	1271.31
Wind (onshore)	20	1153.0	39.6	1095.5	1026.3
Wind (offshore)	20	2550.0	108.1	669.6	641.7
Photovoltaics	20	697.0	11.7	604.5	558.0

*The cost estimations are based on the projections of current and prospective costs of electricity generation (Schröder et al. 2013) and adjusted to the trends given in De Vita et al. (2018)

Table 6 Marginal abatement costs in 2030 (data behind Fig. 5)

		DE	FR	GB	NL	BE	DK	LU	PL	CZ	AT	CH	IT	ES	NO	IE	PT
2030	c_0	49.35	55.47	55.47	44.95	59.17	23.07	49.48	70.18	42.97	55.47	13.72	68.12	39.35	2.22	55.47	45.14
2030	c_de	79.19	71.11	73.32	60.05	66.62	29.53	70.28	80.65	41.29	71.11	16.9	86.3	49.73	2.22	72.51	55.87
2030	c_gb	49.35	55.47	55.47	44.95	59.17	23.07	49.48	70.18	42.97	55.47	13.72	68.12	39.35	2.22	55.47	45.14
2030	c_fr	49.48	61.73	60.83	47.82	60.83	25.05	49.6	70.81	43.09	55.61	14	68.27	42.13	2.22	60.83	48.01
2030	c_1	80.4	79.73	79.73	62.76	68.61	31.7	66.98	81.99	41.31	73.04	17.23	88.95	52.66	0.53	75.9	65.12
2030	c_2	50.09	56.45	56.45	50.09	61.14	37.81	50.19	69.71	42.16	56.23	14.36	76.31	56.45	2.22	56.45	62.81
2030	c_3	80.4	76.09	77.8	66.23	70.96	45	69.44	82.28	41.6	73.69	18.06	89.6	73.69	0.64	76.09	80.62
2030	c_4	51.52	68.11	61.78	51.52	63.3	41.17	51.56	70.34	42.41	57.71	14.41	92.31	61.78	2.02	63.91	68.32
2030	c_n	80.4	80.4	80.4	67.07	72.16	47.18	70.33	82.28	41.62	73.69	18.51	89.85	73.79	0.65	80.4	80.72

Code availability Not applicable.

Author contributions Kristina Govorukha: conceptualization, writing—original draft, writing—reviewing and editing, original draft preparation, visualization, investigation, methodology, software, data curation, formal analysis, project administration. Philip Mayer: writing—original draft, writing—reviewing and editing, data curation, visualization, formal analysis. Dirk Rübbelke: supervision, writing—original draft, writing—review and editing, validation.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Data Availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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