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# How to deal with the risks of phasing out coal in Germany

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## ACRONYMS

CPO: coal phase-out

CPF: carbon price floor

CSP: concentrating solar power

EU ETS: European Union emission trading system

EUA: EU ETS allowances (for the stationary sector)

LIMES-EU: Long-term investment model for the EU electricity sector

LRF: Linear reduction factor (for the EU ETS cap)

MSR: Market stability reserve

PV: photovoltaic

TNAC: total number of allowances in circulation

vRES: variable renewable energies (i.e., onshore/offshore wind, PV and CSP)

## 1. INTRODUCTION

If Germany is to achieve its mid-term (2030) and long-term (2050) climate targets, power production from coal in the country must be substantially reduced and eventually completely phased out. In 2010, the German government formulated the target to reduce greenhouse gas (GHG) emissions by 40% by 2020, 55% by 2030, 70% by 2040, and 80-95% by 2050, relative to 1990 levels (BMWi and BMU, 2010). According to the most recent estimations, the country is bound to miss the 2020 and the 2030 targets by 7 and 13 points respectively (BMU, 2019). Yet, in the past decade, it has become clear that the 2020 target – as well as subsequent targets – will not be met. As a consequence, the German government devised an action plan to reach the 2050 and intermediate targets (BMUB, 2016). This plan includes sector-specific targets for 2030, and proposed measures for achieving them. The energy conversion sector plays a particularly important role: in 2016, it accounted for 37% (332 Mt) of all GHG emissions in the country. Within this sector, the lion's share of emissions came from coal power generation. In 2016 lignite and hard coal-fired power plants emitted 249 Mt$CO_2$, equalling 81% of the total $CO_2$ emissions of the German electricity sector: 51% from lignite and 30% from hard coal (BMWi, 2018). Moreover, some of Germany's coal plants (~11 GW) were only built in the last decade to replace the nuclear plants that will be phased out in the coming years (Pahle, 2010).

In response to these values, in June 2018 the government set up a commission to propose measures to achieve the 2030 target and an "end date" for the use of coal (Die Bundesregierung, 2018). In its final report[1] published in January 2019, the Commission recommended a decommissioning path for all coal power plants. Overall, coal capacity is to be reduced to 17 GW by 2030, and coal to be phased out completely by 2038. The Commission further proposes that the regulator and plant owners decide which plants to phase out when through bilateral agreements (see p. 63 in the Commission report). The government endorsed the Commission's proposal in the "Climate action program 2030", adopted in September 2019, – and complemented it by increasing the target of renewable power production to 65% by 2030.

Yet a mandated national phase-out comes with two significant risks. A first risk relates to the uncertainty of achieving the national climate target. Phasing out capacity is only an indirect control of production and thus emissions, and the remaining coal and natural gas production, may well overshoot the emission limit for 2030. Earlier analysis (Matthes el. 2019) suggests that this may not be the case when renewable production indeed increases to 65%. Given the

[1] The report suggests lignite and hard coal each reach a capacity of 15 GW by 2022, 9 GW of lignite and 8 GW of hard coal by 2030, and the complete decommissioning of both technologies by 2038 (or 2035 is possible). See the complete report in https://www.bmwi.de/Redaktion/DE/Downloads/A/abschlussbericht-kommission-wachstum-strukturwandel-und-beschaeftigung.pdf?__blob=publicationFile

current challenges, in particular for deploying wind onshore, achieving this target cannot be taken for granted. Faced with these challenges, we analyse the risk of achieving the 2030 target in case (*a*) the higher renewable target will be met, and (*b*) just the old target will be met.

As a measure to manage this risk, we analyse a national carbon price floor (CPF [2]) as a potential – yet so far still counterfactual – alternative to the direct capacity phase-out. A CPF, implemented as a national support price on top of the EU allowance (EUA) price, has been suggested by Agora and IDDRI (2017), Edenhofer and Schmidt (2018), and Matthes et al. (2018)[3]. There are many advantages to this measure (see Edenhofer and Pahle, 2019). (*a*) A unilaterally implemented carbon price[4] – regardless of the future EUA price – can be set high enough to reach Germany's national target; (*b*) a CPF price is more cost-effective than phasing out coal through a command-and-control approach; (*c*) a CPF price follows the popular polluter-pays-principle and would not require compensation for plant owners.

We undertake this analysis – CPF, but no direct phase out –to provide policymakers with relevant information in case they reconsider policy choices in the future. A carbon price floor has become an increasingly popular policy recently. The effectiveness of carbon pricing has been demonstrated by the rising ETS prices, and a consequent, substantial reduction in coal generation (Bloomberg, 2019). Furthermore, given the tight margin within which the 2030 climate is to be achieved, policymakers may want to implement a sufficiently high CPF to err on the side of caution. Accordingly, implementing a carbon price floor can become both more viable and appealing – calling for an analysis of its effects.

A second risk is that unilateral action, in general, leads to a 'waterbed effect' in the EU's Emission Trading Scheme (ETS). The waterbed effect in this instance, describes the offset of

[2] Such a policy was implemented in the UK in 2013. Thus far it has proved to be successful in displacing coal generation in favour of more gas generation (Leroutier, 2019; Staffell, 2017).
[3] A CPF was also endorsed by some members of the Coal Commission in a "Sondervertum".
[4] See Hermann et al. (2017) for a legal assessment.

emission reduction initiatives in one Member State by additional emissions in other Member States, given the implementation of an EU-wide cap. This form of leakages has been described by the Netherlands Environmental Assessment Agency (2008), Goulder and Stavins (2011), and Edenhofer et al. (2017). Importantly, it undermines the integrity of the EU ETS. If strong enough, over time, it may lead to a downward spiral that can put the existence of the EU ETS at risk (Pahle et al., 2018). Here the risk-managing is to delete certificates[5], and accordingly, we analyse the amount that would be needed to neutralise the waterbed effect.

The purpose of the paper is to quantify these risks using the numerical power market model LIMES-EU and to consider different options for dealing with them. We first assess if the capacity phase-out achieves the German 2030 climate target for electricity generation, and alternatively which national carbon price floor would be needed. Accordingly, we concentrate on that particular year. We then conduct a comprehensive sensitivity analysis to determine the range of this price under different assumptions for uncertain policy and economic parameters. As part of that, we also provide a back-of-the-envelope calculation of the avoided costs of compensation vis-à-vis the Coal Commission proposal.

Subsequently, we focus on the risks for the EU ETS related to the waterbed effect, analysing the period until 2050 because the ETS cap decreases significantly (at least 80%). We acknowledge that there is substantial market and policy uncertainty in the long term, and in particular further ETS amendments could alleviate a potential waterbed effect. However, our intention is not to predict the future, rather, bring to policymakers' attention potential problems that may need consideration when planning further action. We consider two options for addressing the waterbed effect: (*a*) multilateral cooperation with other ambitious countries like France and the Netherlands that are also willing to implement such a CPF on a national or regional basis (Carbon Market Watch, 2017; Reuters, 2018); and (*b*) cancellation of allowances

[5] This measure was also proposed by the Coal Commission, but not adopted by the government.

in line with the provisions introduced in the recent reform of the EU ETS[6] (Market Stability Reserve (MSR), national level). The first option has potential to reduce the waterbed effect and is also attractive as a policy sequence (Pahle et al., 2018) that could lead to an EU-wide approach to climate policy in the future. Edenhofer and Schmidt (2018), and Matthes (2017) describe such a sequence. Our working hypothesis is that a well-designed coal phase-out in Germany does not undermine the EU ETS in the mid-term, and could even enable an EU-wide approach after 2030. The facilitation of an EU-wide approach seems essential in the long-run, and any national action that would not encourage this would be in vain. We will come back to this in the conclusions.

Our work relates to two strands of literature: First, the strand that addresses overlapping policies and policy interaction between the EU ETS and national policies. See Fischer and Preonas (2010) for theoretical considerations and a review of the early literature. Numerical work in the last years has focussed mainly on renewable policies, e.g. Weigt et al. (2013) and Van den Bergh et al. (2013). The second strand of literature covers scenario analyses of the German coal phase-out. Nearly all of this work, which we review in more detail in the following section, is grey literature and has been conducted specifically in the context of the German policy debate. This literature deals superficially with EU ETS policy interactions, like the assumption that ETS prices are exogenous. Both literature strands put very little emphasis on the risks that come with policy design and interactions.

Our study goes beyond the existing literature in the following ways: (*a*) we analyse the German coal phase-out specifically from a risk perspective and examine ways of dealing with these risks, which is crucial for making the right policy choices. To assess the risk of over- or undershooting the national climate target, we conduct a comprehensive sensitivity analysis, which also considers the future role of the industry sectors covered by the ETS – a step

[6] See more detail in Appendix A.

neglected in previous work. (*b*) We rigorously consider policy interaction with the EU ETS and the related risks that come with national approaches. We do this by separating the different components of the waterbed effect, as alluded to by Begemann et al. (2016) and Sandbag (2017): the trade-related waterbed effect "in space" that arises from an immediate relocation of production to other markets; and the waterbed effect "in time", which results from lower demand for allowances and the corresponding banking of allowances for future use. The implications of the waterbed effect "in time" are particularly under-researched, which is why (in contrast to most other studies) we analyse the full ETS time horizon up to 2050. (*c*) We consider how cancellation of the MSR from 2023 could reduce the waterbed effect, as analysed by Perino (2018), Burtraw et al. (2018), and Pahle et al. (2018).

The paper is organised as follows: Section 2 summarises the main studies and papers dealing with the coal phase-out in Germany; Section 3 describes the model, the main assumptions and the different scenarios; Section 4 discusses the results. Finally, in Section 5, we conclude and provide the main insights from our research.

## 2. LITERATURE REVIEW

The work addressing the coal phase-out in Germany varies widely in terms of approach and sectors covered. Importantly, almost all of the recent studies are grey literature that deal with the economic questions of policy interaction relatively superficially. Table 1 summarises the studies focused on determining an exogenous phase-out schedule based on different allocation rules. These studies, except Matthes et al. (2019), were nonetheless carried out before the Coal Commission delivered its final report.

Matthes et al. (2019) analyse the decommissioning path proposed by the Coal Commission. The study assumes a high deployment of renewables to reach a share of 65% by 2030. There is limited waterbed effect since the authors assume that carbon prices remain unchanged for their baseline scenario, due to the cancellation of sufficient certificates carried out by Germany. Although there are fewer certificates available, the gap left by coal-fired decommissioned plants in Germany encourages fossil-based production abroad. The resulting European rebound effect is 32% in 2030. This is an important reference point for our work, upon which we elaborate further in our results analysis.

*Table 1. Selected studies and papers analysing the impact of a regulated coal phase-out in Germany.*

| Study | Type of study [a] | Sector | Region | Time horizon | $CO_2$ price | Coal phase-out (CPO) | |
|---|---|---|---|---|---|---|---|
| | | | | | | **Scenario/Criteria** | **If CPO completed, when?** |
| Agora Energiewende (2016) | GL | Electricity | most countries EU | 2015-2040 | 13 €/t$CO_2$ in 2020 to 39 €/t$CO_2$ in 2040 | Ref: 40y Hard coal and 50y lignite lifespan | -- |
| | | | | | | Coal Consensus Path 2040: Remaining plant lifespans | 2040 |
| Matthes et al. (2017) – WWF | GL | Electricity | most countries EU | 2015-2050 | 10 €/t$CO_2$ in 2020 to 60 €/t$CO_2$ in 2050 (exogenous) | Transformation: 30y lifespan and EPS between the 21th and the 30th year of 3.35 t$CO_2$/Kwh | 2035 |
| | | | | | | Other 7 scenarios with lifespan of <20y-30y | before 2050 in all the cases |
| Pietroni et al. (2017) - Greenpeace | GL | Electricity | most countries EU | 2015-2030 | Increase from 10 to 35 €/t$CO_2$ in 2030 (from WEO, 2016) | Ecologic merit-order (most inefficient plants are decommissioned first) | 2030 |
| Heinrichs et al. (2017) | PR | Energy | Germany | 2015-2050 | 15 €2015/t$CO_2$ (2020) to 37 €2015/t$CO_2$ (2050) (from WEO, 2014) | 50y lignite and 45y hard coal | -- |
| | | | | | | Path from (Klaus et al., 2012) | 2040 |
| | | | | | | FPO: from survey | 2020 |
| Heinrichs and Markewitz (2017) | PR | Energy | Germany | 2015-2050 | 15 €2000/t$CO_2$ (2020) to 30 €2000/t$CO_2$ (2050) (from WEO, 2015) | 50y lignite and 45y hard coal | -- |
| | | | | | | Path from (Klaus et al., 2012) | 2040 |

| Study | Type of study [a] | Sector | Region | Time horizon | $CO_2$ price | Coal phase-out (CPO) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Scenario/Criteria | If CPO completed, when? |
| Enervis Energy Advisors (2015) - Agora | GL | Electricity | EU | 2015-2040 | 13 €/t$CO_2$ in 2020 to 39 €/t$CO_2$ in 2040 (from WEO, 2014) | Ref: 40y Hard coal and 50y lignite lifespan + 10y retrofit possible if economically profitable | -- |
| | | | | | | No-retrofit: As Ref, but only with original lifespans | -- |
| | | | | | | Climate scenario: early decommissioning based on the $CO_2$ abatement costs of the plants necessary to reach the emission reduction path | -- |
| Klaus et al. (2012) - Greenpeace | GL | -- | -- | -- | -- | Coal-based generation is capped, and production certificates are allocated based on efficiency | 2040 |
| Matthes et al. (2019) | GL | Electricity | EU | 2017-2030 | 23 €/t$CO_2$ in 2019, increasing linearly to 27.3 €/t$CO_2$ in 2025, and constant until 2030 | Coal Commission phase-out path | 2038 |

[a] GL: Grey literature; PR: Peer-reviewed paper

Apart from the study by Matthes et al. (2019), the waterbed effect gets limited attention in the studies mentioned in Table 1. Although Agora Energiewende (2016) warns about the need to reform the EU ETS to avoid the waterbed effect, it is not assessed. Enervis Energy Advisors (2015) calculates that a 50% emission reduction in Germany would be offset by an increase in other EU countries, but it is unclear to which time horizon this corresponds.

The waterbed effect receives more attention in the studies that explore the effects of a $CO_2$ price for Germany or a coalition of countries. Four studies were identified (see Table 2) in which at least Germany implements a higher $CO_2$ price than the rest of the EU - all have a time horizon no longer than 2030. Only in one study (Matthes et al., 2018) is the impact of a coalition evaluated (countries of centre-western Europe (CWE)).

These studies focus primarily on exploring different price levels to identify those that allow the German target (emission reduction of 40% in 2020 and 61% in 2030) to be reached. There is little discussion about how these levels may be affected by uncertainties and where the risks lie. The intertemporal price formation in the EU ETS is also omitted in the static nature of the approaches. More precisely, these studies neglect the intertemporal price formation because of the possibility to bank allowances. Using more or fewer allowances in one year can influence prices in other periods, giving rise to a waterbed effect over time.

The effective $CO_2$ prices in these studies lie between 15 and 80 €/t$CO_2$ in Germany and between 5 and 30 €/t$CO_2$ in the rest of the EU. 75 €/t$CO_2$ is the largest carbon price support applied in Germany. The wide range of $CO_2$ prices highlights the uncertainty about the evolution of the EU ETS, even in the medium term. The resulting German power sector emissions would lie between 102 and 262 Mt$CO_2$ by 2020, implying a reduction of 28-72% compared to 1990 levels. In Table 2, the waterbed effect in a specific year is measured as the ratio between the increase of non-German emissions (for a reference scenario) and the reduction in German emissions (for the same reference scenario, whose assumptions depend on each study). Values range between 24 and 70%.

*Table 2. Selected consultant studies (no peer-reviewed studies available) analysing the waterbed effect due to $CO_2$ floor price implementation in Germany.*

| Study | Modelled year | Effective carbon price (€/$tCO_2$) | | Emissions in Germany ($MtCO_2$) | Coal production in Germany (TWh) | | Waterbed (%) | Germany electricity net importer? |
|---|---|---|---|---|---|---|---|---|
| | | Germany | Rest of EU | | Lignite | Hard coal | | |
| Matthes et al. (2018) – WWF | 2020 | 15-35 | 5.6 | 158-254 | 26-105 | 27-56 | 48-70 | If $CO_2$ price >15 |
| | | 15-35 in CWE[a] | 5.6 | 193-262 | 51-105 | 44-64 | 24-54 | If $CO_2$ price >15 |
| Hermann et al. (2017) - UBA | 2025 | 37 | 27 | 230 | 106 | 47 | ND | No |
| | 2030 | 47 | 37 | 180 | 78 | 32 | 56 | No |
| Huneke and Perez Linkenheil (2016) – Brainpool | 2030 | 50 or 75 | 27.6 | 144-226 | ND | ND | 60 | Yes |
| Fernahl et al. (2017) - BEE | 2020 | 25-80 | 5 | 102-197 | 38-95 | 30-58 [b] | 57-64 | Yes |
| | 2025 | 37-80 | 17 | 114-249 | 58-110 | 50-102 [b] | 54-67 | Yes |
| | 2020 | 30 | 20 | 229 | 90 | 65 | ND | No |
| | 2025 | 45 | 30 | 223 | 100 | 80 | ND | No |

"ND" accounts for "not defined": data not reported in the studies.

[a] CWE corresponds to FR, BE, NL, LU, AT, DE, DK.

[b] Intervals correspond only to scenarios in which Germany implements a $CO_2$ tax of either 20 or 40 €/$tCO_2$. Data is not available for the rest of scenarios.

In addition to the waterbed effect, the studies highlight the reduction of net electricity exports in Germany. In all studies, when the difference between the effective $CO_2$ price in Germany and that of the EU is higher than 15 €/t$CO_2$, Germany becomes a net importer. For instance, a carbon price support of 40 €/t$CO_2$ could lead to net imports of roughly 145 TWh/yr in 2025 (Fernahl et al., 2017). This would break the trend of Germany as a net exporter, which has been the case since 2003. 54 TWh of net exports were observed in 2017 (BMWi, 2018).

Other studies only modelled parts of the EU when analysing the impact of different policies aimed at reducing emissions. Some of them focused on the waterbed effect. For instance, assuming different ETS prices and hydro availability, Višković et al. (2017) estimate that carbon leakage would range between 6 and 40% in southeast Europe. Brink et al. (2016) compare different supporting policies, which aim to increase the stringency of the EU ETS. Their analysis shows a full temporal waterbed effect by 2030 when all EU ETS members implement a carbon price floor of 20 €/t$CO_2$. Other studies focus on the interaction between different policies, particularly renewables support and the EU ETS. For instance, Müsgens (2018) assesses that subsidies for RES are required to reach a RES share of >50% by 2050, as the ETS prices alone would not be enough to trigger such investments. Weigt et al. (2013) estimate that carbon emission abatement is higher when a renewable support policy is in place, simultaneously to the ETS. Abrell et al. (2017) analyse the interaction between the ETS and non-ETS sectors when a carbon price floor is implemented in the ETS, and there is a fixed overall target. According to their study, a carbon price floor of 50-75 €/t$CO_2$ in the ETS leads to the overall lowest costs of climate policy (20-30% lower than the current policy scenario). However, very high carbon price floor prices lead to higher policy costs (e.g., a price of 120 €/t$CO_2$ would lead to welfare costs up to 10% higher than the current policy scenario) as further (inefficient) abatement in the ETS is carried out, while cheaper abatement in the non-ETS is not utilised. Likewise, Jarke and Perino (2017) determine that a renewable support policy in a capped sector leads to carbon leakage to a non-capped sector within the same economy.

## 3. METHODS

In this section, we describe the main characteristics of the LIMES-EU model used in this paper and explain the iterative process used to estimate ETS prices in the presence of a group of countries implementing a carbon price floor. We then present the main data sources and assumptions. We derive an electricity-only cap within the EU ETS as only the electricity sector is included in our model. The section concludes with a presentation of the scenarios analysed.

### 3.1. Model description

LIMES-EU is a linear optimisation model that computes electricity dispatch, and calculates generation and transmission capacity expansion in five-year steps from 2010 to 2050 for 29 regions in Europe, (28 countries and a region aggregating the Balkan countries) at the minimum cost. Costs are intertemporally minimised, i.e., we assume perfect foresight. For each of these years, six representative days are modelled via demand profiles and variable renewable energies (vRES) availability profiles. For each day, eight blocks of three hours are assumed, leading to 48 time slices. These slices are estimated using a cluster algorithm that takes into account the correlation between demand and vRES generation in the different EU countries. This allows 95% of wind variability to be captured with six representative days (Nahmmacher et al., 2016). LIMES-EU thus captures intra-day demand and supply variability, which allows the short-term variability effects on long-term investment decisions to be analysed. The model contains 32 storage and generation technologies, including different vintages for lignite, hard coal and gas. The data sources for the main parameters used in the model are described in Appendix B[7].

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[7] Detailed documentation of LIMES-EU is available at: https://www.pik-potsdam.de/research/transformation-pathways/models/limes/limes-documentation-2018/view (version December 2018)

LIMES-EU considers several standard constraints, e.g., capacity constraints, resource constraints (e.g., biomass potentials and wind/solar/hydropower availability depending on historical data) and operating constraints (e.g., minimum load and ramping conditions for each technology). LIMES-EU also considers selected EU-wide national climate and energy policies, such as the capacity targets of the National Renewable Energy Action Plans (NREAPS) for 2020 (European Commission, 2013).

Policies can be implemented in LIMES-EU either as quantity restrictions (e.g. coal phase-out) or cost changes (e.g. emission tax). The national carbon price support is implemented as an additional cost component in the model. However, finding the appropriate level of support that ensures the ETS allowance price, plus the national carbon price support, equal a carbon price floor, is challenging, because of the waterbed effect. Implementing a carbon price reduces the initial ETS price, which in turn implies a higher carbon price and so forth. This dilemma is solved using an iterative process that is explained in detail in Appendix C.

The model is calibrated to 2015 data by fixing the generation and transmission capacities to capacities that existed at that time (see Appendix D for a comparison between modelled and historical emissions and generation). We run the model in GAMS and use CPLEX as solver.

## 3.2. Background assumptions for all scenarios

We implemented climate, energy, and security of supply policy targets by including constraints on $CO_2$ emissions or on the deployment of certain technologies as follows:

- As LIMES-EU is an electricity sector model, we only cover that portion of the EU ETS and estimate an electricity-only cap decreasing from 892 $MtCO_2$ in 2020 to 77 $MtCO_2$ in 2050. This cap amounts to a cumulated budget of 16 $GtCO_2$ (see Appendix 0 for a detailed calculation).

- We account for the MSR implicitly by setting the market surplus (bank) to zero in the initial period (year 2020 in the model), which spans 2018 to 2022. We do this based on the assumption that the amount of certificates that will be cancelled by 2023 is of the same order of magnitude as the current market surplus[8].
- Germany has to achieve its legally binding RES targets (EEG) of 40% in 2025, 55% in 2035 and 80% in 2050 (BMWi, 2017). We interpolate these values for the remaining years of our time-horizon. For other countries, we do not assume any RES target.
- We do not allow for CCS deployment. Worldwide technological innovation to use captured $CO_2$ for commercial purposes seems unlikely in the medium-term (IEA, 2016). Thus far, there are no large-scale power plants with integrated CCS in Europe[9]. However, we consider CCS in the sensitivity analysis (see Appendix E).
- In line with the countries' plans or policies, a progressive nuclear phase-out is completed in Belgium by 2025, in Germany by 2022 and in Switzerland by 2044.
- Investments in coal-fired plants are only allowed in Poland, Greece and the Balkans, as these countries did not support the sector's public statement of refraining from building coal-fired power plants after 2020 (EURELECTRIC, 2017).
- Countries implement measures to ensure secure power system operations by having sufficient overcapacity for an emergency. A 10% capacity margin is assumed, i.e.

[8] By the end of 2016, the certificate surplus was about 1.7 billion EU allowances (EUA) (EEA, 2017a). According to Perino (2018), in 2019 the MSR is expected to receive 1.45-1.6 billion EUA. By 2023, they estimate that 1.7 billion EUA will be cancelled.

[9] According to the IPCC (2014), achieving mitigation scenarios that reach about 450 ppm $CO_2$-eq in 2100 (consistent with a likely chance to keep warming below 2°C) is unlikely without CCS. Costs would increase up to 138%. However, thus far there is little development of CCS projects, in particular in power generation. There are only two operating projects in the world as of May 2018 (*Boundary Dam Carbon Capture and Storage* in Canada and *Petra Nova Carbon Capture* in USA). The only project in Europe, *Caledonia Clean Energy*, a gas power plant in UK, is at an early development stage and is expected to start operating in the 2020s (Global CCS Institute, 2018). The European Commission (2017) reported that all assessments of carbon capture, transport and storage projects (29 from seven countries) turned out to be economically infeasible. In countries like Germany there is also strong public opposition toward CCS (Jungjohann and Morris, 2014). Recently, five German federal states have prepared decisions or have passed laws limiting or banning underground storage of $CO_2$ (European Commission, 2017).

available capacity (after applying derating factors to the generation technologies and transmission capacity) has to exceed demand by at least 10% at any time.

- The discount rate is 5%, and internal transmission/distribution losses account for 8%.

### 3.3. Scenario setup

For the reference scenario (*REF*), we assume that the only emission-related policy in place is the EU ETS. We first analyse the impact of the CPO pathway proposed by the Coal Commission under two RES scenarios: a "trend" scenario with a RES target of 47.5% by 2030 (*CPO_RESbase*) and an "aspirational target" in which RES should achieve at least 65% share of gross demand by 2030 (*CPO_RES+*). In the counterfactual policy scenarios *onlyDE,* we assume that only Germany implements a CPF, which increases linearly by 3€/year from 30 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050. We initially focus on the impact of Germany being the only country that implements such a measure. Multiplying by a factor *X*, we vary the "default" price path between a range of 50-100%. Using these values, we run additional iterations *onlyDE_X*. Moreover, in the CPF scenarios, we only mandate the "trend" development for renewables leading to a share of 47.5% in 2030 (see above). This is because we want to provide a robust estimate for the CPF level necessary to reach the 2030 climate target.

We then analyse the impact of different coalitions of countries implementing the default price path. The 'climate coalition' (*ClimaCoalition*) includes most of the countries that have pledged to reduce coal in the medium-term (countries that have signed the Past Coal Alliance[10]) and Germany. The members of this coalition were chosen for the sake of the analysis rather than for political reasons. In the scenario *allEUETS,* we considered that all EU ETS members implement the specific carbon price floor. In two additional scenarios with the same carbon

[10] See the declaration and list of members as of July 2019 at: https://www.gov.uk/government/publications/powering-past-coal-alliance-declaration

price floors (*onlyDE_c* and *ClimaCoalition_c*), we assumed that countries can cancel allowances to avoid carbon leakage to non-members of the coalition. The certificates to be cancelled were estimated as the difference between the emissions of the respective coalition members in the reference scenario *REF* and each of the *onlyDE* - *ClimaCoalition*. These certificates were subtracted from the original cap in scenarios *onlyDE_c* to *ClimaCoalition_c*. In all the CPF scenarios, we assume the "trend" RES target, i.e., 47.5% by 2030. See Table 3 for a summary of the scenarios evaluated.

*Table 3. Scenarios description.*

| | | **Coal phase-out (and 2030 RES share of)** | | **Countries implementing a carbon price floor (from 30 €/$tCO_2$ in 2020 to 120 €/$tCO_2$ in 2050)** | | |
|---|---|---|---|---|---|---|
| **Certificates cancellation** | **--** | **47.5%** | **65%** | **DE** | **Nordic, GB, IE, DE, Benelux, AT, CH, FR, IT, PT** | **All EU ETS members** |
| **Not allowed** | *REF* | *CPO_RESbase* | *CPO_RES+* | *onlyDE* | *ClimaCoalition* | *allEUETS* |
| **Allowed** | -- | -- | -- | *onlyDE_c* | *ClimaCoalition_c* | -- |

*Benelux: Netherlands, Belgium, and Luxemburg.

**Nordic: Sweden, Norway, Denmark, and Finland.

For European countries not belonging to the EU ETS (Switzerland and the Balkans), we assumed exogenous carbon prices. We assumed that Switzerland implements a carbon tax equal to the ETS carbon price in the scenarios *REF* and *onlyDE*, and the default carbon price floor path for scenarios *ClimaCoalition* and *allEUETS*. The Balkans apply a carbon price, increasing linearly from 5 €/$tCO_2$ in 2020 to 23 €/$tCO_2$ in 2050. We also assume that the UK remains within the EU ETS and keeps a carbon price floor of 20 €/$tCO_2$ in 2020 in all scenarios.

We perform a sensitivity analysis on our reference scenario (see Appendix E). First, we evaluate the impact of policy and economic parameters with a high level of uncertainty, e.g. the ETS electricity-only cap, fossil fuel prices, vRES capital costs, cross-border transmission expansion, discount rate, electricity demand, the prices in UK and Balkan. We also consider how results may change if CCS was available. Second, we evaluate the impact of rather modelling parameters (capacity margin, transmission losses, and the number of representative days). We provide additional detail for the modelled representative days by showing their impact on carbon prices, emissions and investments in main technologies.

## 4. RESULTS

The European electricity sector is modelled with the implementation of different carbon price floors. In this section, we first present the results of our analysis on the impacts of only Germany implementing different carbon price floor levels. Following this, we perform a sensitivity analysis to determine the required price to reach the target in 2030 under different assumptions. We then present the impact of different coalitions of countries implementing a carbon price floor, focusing on emissions and coal generation in Germany and the EU ETS. The section concludes with the simulation of the MSR to estimate the volume of certificates that would need to be cancelled to avoid the waterbed effect.

### 4.1. Impact of a coal capacity phase-out or different carbon price floors in Germany

This section examines the effect of either a command and control coal phase-out or different carbon price floor paths on the achievement of Germany's 2030 targets. The command and control coal phase-out is based on the decommissioning path proposed by the Coal Commission. The carbon price floor paths are a fraction (50-100%) of the default price (from 30 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050), e.g., the scenario *onlyDE_50* refers to a price path of 15 €/t$CO_2$ in 2020 to 60 €/t$CO_2$ in 2050. In Figure 1, we present the *CPO** scenarios and a selection of price paths, focusing on the resulting coal generation, emissions and ETS price in 2030. The values for 2015 are presented to give an idea of the magnitude of emission reductions. For practical purposes, we use "effective carbon price" for the total amount charged per t$CO_2$ to polluters, i.e., the sum of the ETS price and the carbon price support.

According to Figure 1, German emissions and coal generation decrease considerably in 2030 in all evaluated scenarios - even when Germany does not implement a carbon price floor (*REF*) - with respect to 2015 values. Still, the ETS alone would be insufficient to decrease German emissions down to the national target level for 2030. If Germany does not implement any further emission policy (*REF*), the ETS price is 23 €/t$CO_2$. Although this price would cut emissions to 191 Mt$CO_2$ (almost 50% lower than in 1990), it would not be enough to reach the emission targets for electricity generation (roughly 147 Mt$CO_2$, see the details of the target estimation in Appendix B).

Likewise, when the command-and-control phase-out takes place, the emission target is narrowly missed even when, additionally, RES deployment is larger (*CPO_RES+)*. There is a small difference between emissions in the two scenarios *CPO_RESbase* and *CPO_RES+* due to the RES expansion. In *CPO_RESbase,* the "default" target of 47.5% is not binding, and indeed the share by 2030 reaches 56%. Furthermore, the higher RES generation in *CPO_RES+* mainly displaces gas generation and net imports. Therefore, a carbon price floor would be required for Germany to reach its 2030 target even in the case of a regulated coal phase-out. Through additional calculations, we estimate that the required carbon price for Germany would be 29 and 27 €/t$CO_2$, respectively in *CPO_RESbase* and *CPO_RES+*.

Our results also show that ETS price is always lower than the carbon price floor evaluated, and thus the effective carbon price in Germany (ETS price plus national carbon price support) equals the carbon price floor. The higher the carbon price floor, the higher the spread between the German effective $CO_2$ price and the ETS price, and thus the larger are the differences in emissions and coal generation between *REF* and *onlyDE_X*. This gap is because the higher $CO_2$ price in Germany makes German electricity generation from coal less competitive. In 2030, coal generation decreases by between 25 TWh/yr (*onlyDE_50*) and 96 TWh/yr (*onlyDE_100*). Accordingly, emissions decrease by between 26 $MtCO_2$ (*onlyDE_50*) and 98 $MtCO_2$ (*onlyDE_100*) with respect to *REF*.

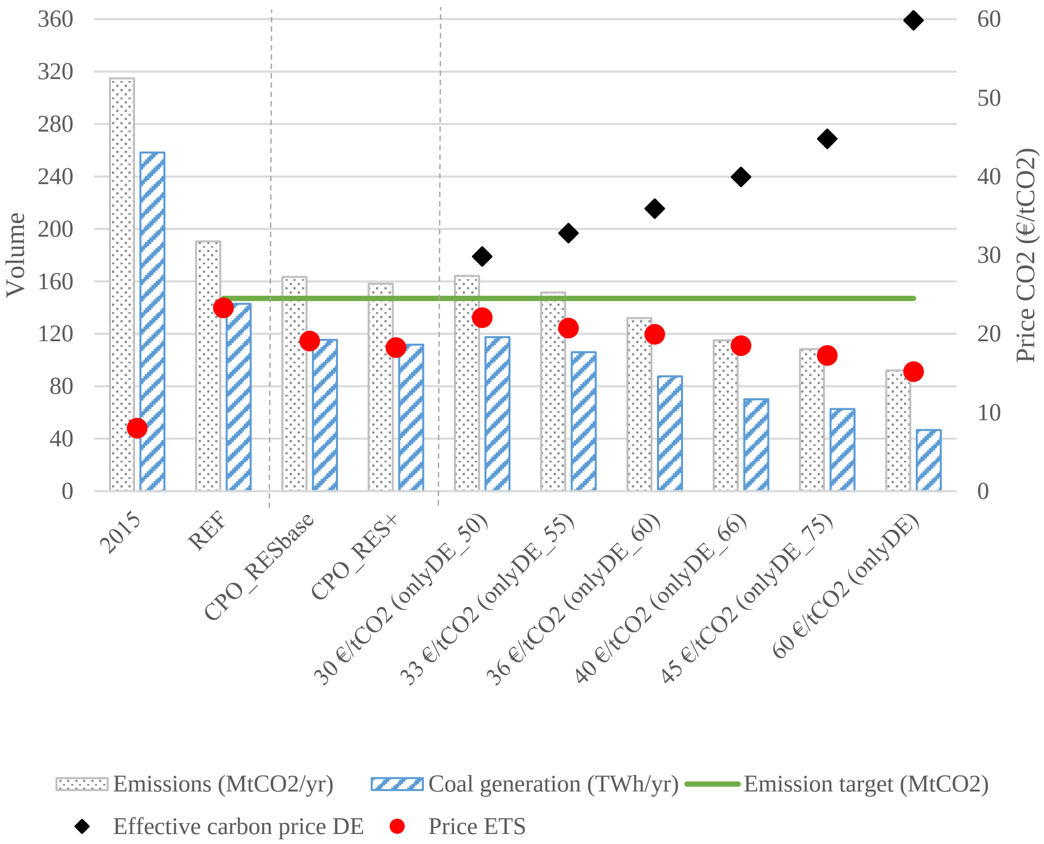



*Figure 1. Emissions from electricity generation and coal generation as compared with the effective $CO_2$ price in Germany and the ETS price in 2015 and under different carbon price floor scenarios in 2030.*

Based on our results, we conduct a back-of-the-envelope calculation for the compensation to coal power plant owners as recommended by the Coal Commission. More specifically, even without any additional measures in 2030, ETS prices lead to a (market-driven) reduction of coal capacities to 11.6 GW (hard coal) and 12.0 GW (lignite), respectively. The Coal Commission recommends shutdowns to reach 8 GW (hard coal) and 9 GW (lignite) in the same year. This means 3.6 GW of hard coal and 3 GW of lignite capacity would also need to be shut down in addition, and thus receive compensation that – depending on the rules for calculating the compensation – would amount to up to 4 billion €[11].

From Figure 1, Germany would need to implement a carbon price floor between 33 €/t$CO_2$ and 36 €/t$CO_2$ to reach the target level. Additional calculations allows us to estimate an exact price of 34 €/t$CO_2$ at default assumptions. Although a carbon price of such magnitude encourages investments in renewables[12], the resulting higher RES generation does not entirely offset the drop in coal-based generation because of carbon leakage. The generation-mix in Germany in 2030 changes as follows. Renewable generation in 2030 is 25 TWh/yr higher in *onlyDE_55* than in *REF* (all from wind turbines). Coal and gas generation is 37 TWh/yr and 9 TWh/yr lower, respectively. German generation decreases overall by 22 TWh/yr and thus net imports increase from 33 TWh/yr (*REF*) to 55 TWh/yr (*onlyDE_55*) (In all carbon price floor scenarios Germany becomes a net importer in 2020, as it does after 2025 in *REF*). While German coal generation is 37 TWh/yr lower, total coal generation in the EU ETS decreases only by 16 TWh/yr. This means that coal generation in other Member states increases by 21 TWh/yr because of the lower ETS prices in *onlyDE_55* (21 €/t$CO_2$) than in *REF* (23 €/t$CO_2$). Hence, implementing a carbon price support increases net imports, favouring coal generation in other countries (waterbed effect "in space"). A wider coalition of countries implementing a carbon price floor reduces coal generation abroad. This coalition is evaluated in Section 4.3. In the following section, we estimate the range of the required price in 2030, based on a sensitivity analysis.

[11] The calculation is based on 600 million EUR per GW, the compensation lignite plant owners received for decommission their plants through the so called "Braunkohle Sicherheitsbereitschaft". As carbon prices in 2019 are higher than in 2016 when the Sicherheitsbereitschaft was negotiated, and thus net profits from lignite power plants are lower in 2019 than they were in 2016, compensation for future lignite shutdowns will likely be lower.
[12] The RES target constraint representing the EEG 2017 targets is not binding in any of these scenarios in 2030.

## 4.2. Achieving the target under different assumptions

In this section, we assess the risk related to achieving the German climate target for electricity generation in 2030 (147 $MtCO_2$, see Appendix B for the estimation details). We perform a sensitivity analysis to determine how much the German carbon price required to reach this target would change under different assumptions about uncertain policy and economic parameters. From these results, we can estimate a range for the price Germany requires to reach the 2030 target. The highest required price would thus allow Germany to deal with the potential risks posed by external variables.

We test seven variables whose uncertainty could have major impacts on the EU ETS, and thus on German emissions: the level of the electricity-only cap, fossil fuel prices, vRES capital costs, expansion of cross-border transmission, the coalition's carbon price floor, the discount rate, and the electricity demand. Additionally, we evaluate two scenarios corresponding to the "worst" and the "best" case scenarios. These result from the simultaneous combination of all sensitivity variations that increase/decrease the carbon price required to achieve the 2030 target. We evaluate in total 19 possible outcomes and estimate the range of the effective carbon price required in Germany such that it may reach its 2030 target. The remaining assumptions are the same as for *onlyDE* (only Germany implements a carbon price floor). The main assumptions are as follows:

- Electricity-only cap: the impact of easier/more difficult industry decarbonisation. As described in Appendix 0, to calculate an electricity-only ETS cap, assumptions are needed regarding the future share of the industry and heating sectors. In two variation scenarios representing the difficulty to decarbonise the industry covered by the EU ETS, the 2050 share of ETS certificates required by the industry covered by the EU ETS decreases (increases) from the default value of 55% to 45% (65%), thus resulting in a higher (lower) electricity-only cap. This varies the default budget by 1.6 $GtCO_2$ (10%): the resulting budgets are 17.6 $GtCO_2$ and 14.4 $GtCO_2$, respectively.

- Fuel prices: price ranges were used from the *Sustainable development* and *Current policies* scenarios of the WEO (IEA, 2017a) (see Table E1). Oil, gas and hard coal prices in 2025 and 2040 were inter/extrapolated for the full time horizon.
- vRES capital costs: these vary ±20% after 2025.
- Coalition's carbon price floor: we assumed that Germany implements a carbon price floor high enough to achieve its 2030 target, while the rest of the *ClimaCoalition* members implement a carbon price floor using the "default" price path (a linear increase from 30€/t CO2 in 2020 to 120€/ t CO2 in 2050).
- Cross-border transmission expansion: an extreme scenario was tested in which transmission is maintained at 2015 levels through the entire modelling horizon.
- Discount rate: these vary between 2.5% and 15%.
- Electricity demand: high electricity demand using the highest demand from European Commission (2018) scenarios. Since there is no data at the country-level, we scale our demand profiles based on the EU-level profiles. The resulting demands are 5% and 36% higher in 2030 and 2050, respectively, compared to *REF*.
- "All bad": high gas prices, low coal prices, a low electricity-only cap, expensive vRES, constant transmission, the coalition from *ClimaCoalition* implementing a default price path, a discount rate of 15% and high electricity demand.
- "All good": low gas prices, high coal prices, a high electricity-only cap, cheap vRES, transmission expansion as in *onlyDE* and only Germany implementing a carbon price floor.

Table 4 shows the effective prices in Germany required to reach the emission targets in 2030 for the default case and each of the variations. When we apply individual changes, prices vary from 25 to 51 €/t$CO_2$, the resulting carbon price support varying between 8 and 30 €/t$CO_2$. The required price seems to be particularly sensitive to changes in vRES costs and the discount rate: the highest price required (51 €/t$CO_2$) occurs when this is 15%. High discount rates are symptoms of risk aversion or even a myopic view of investments. These negatively affect new investments, particularly renewables, and thus required carbon prices are higher. Note that the price is also high (44 €/t$CO_2$) when there is no transmission expansion because fossil-based generation, as well as RES with higher availability, (e.g., solar energy from southern countries) is locked-in.

Consequently, imports are limited. Countries with more polluting generation mixes (including Germany) need to invest more in national RES capacity, whose availability is in turn more limited. This trend highlights the importance of encouraging a stronger European integration for more efficient decarbonisation of electricity generation. When we combine all positive (or all negative) variations – which constitutes an extreme scenario – the required price range is wider: between 17 and 87 €/t$CO_2$. In Appendix F, we compare these results with other findings in literature.

*Table 4. Sensitivity analysis for the effective price and the carbon price support needed in Germany to meet the 2030 emission targets.*

| **Scenario** | | **Required effective price Germany (€/t$CO_2$)** | **ETS price (€/t$CO_2$)** | **Carbon price support (€/t$CO_2$)** |
|---|---|---|---|---|
| Base case | | 34 | 21 | 13 |
| Emission cap | High | 32 | 15 | 17 |
| | Low | 35 | 27 | 8 |
| Fossil fuel prices | Low | 34 | 26 | 8 |
| | High | 35 | 16 | 19 |
| | Low gas /high coal | 32 | 17 | 15 |
| | High gas /low coal | 38 | 21 | 16 |
| vRES capital costs | Cheap | 25 | 12 | 13 |
| | Expensive | 41 | 27 | 14 |
| *ClimaCoalition* with default price | | 39 | 10 | 29 |
| Constant transmission | | 44 | 26 | 17 |
| | 2.5% | 27 | 18 | 9 |

| | | | | |
|---|---|---|---|---|
| Discount rate | 7.5% | 39 | 23 | 15 |
| | 10% | 44 | 23 | 21 |
| | 12.5% | 48 | 24 | 24 |
| | 15% | 51 | 25 | 26 |
| High electricity demand | | 38 | 8 | 30 |
| All bad | | 87 | 54 | 33 |
| All good | | 17 | 5 | 12 |

### 4.3. What if Germany is not alone?

We analysed the effect of two differently sized coalitions (see section 3.3) implementing a carbon price floor on emissions and coal generation in Germany and the EU. When a coalition of countries implements a carbon price floor, ETS prices decrease substantially (see Figure 2). In *allEUETS*, as all EU ETS members implement the carbon price floor, the emission banking constraint is non-binding (i.e., the ETS price equals zero). They, therefore, apply a carbon price support equivalent to the carbon price floor. When there is only the ETS (*REF*), the ETS price increases from 14 €/t$CO_2$ in 2020 to 63 €/t$CO_2$ in 2050. When a coalition of countries implements a carbon price floor, the demand for certificates from these countries decreases because fossil-based generation is reduced. This results in lower ETS prices, e.g., 35% and 75% lower in *onlyDE* and *ClimaCoalition* than in *REF*, respectively. The carbon price support for Germany (in *onlyDE*) or the coalition members (in *ClimaCoalition*) implementing the carbon price floor equals the difference between the carbon price floor and the ETS price. For instance, the German carbon price support in *onlyDE* in 2050 would be 79 €/t$CO_2$ (120 - 41).

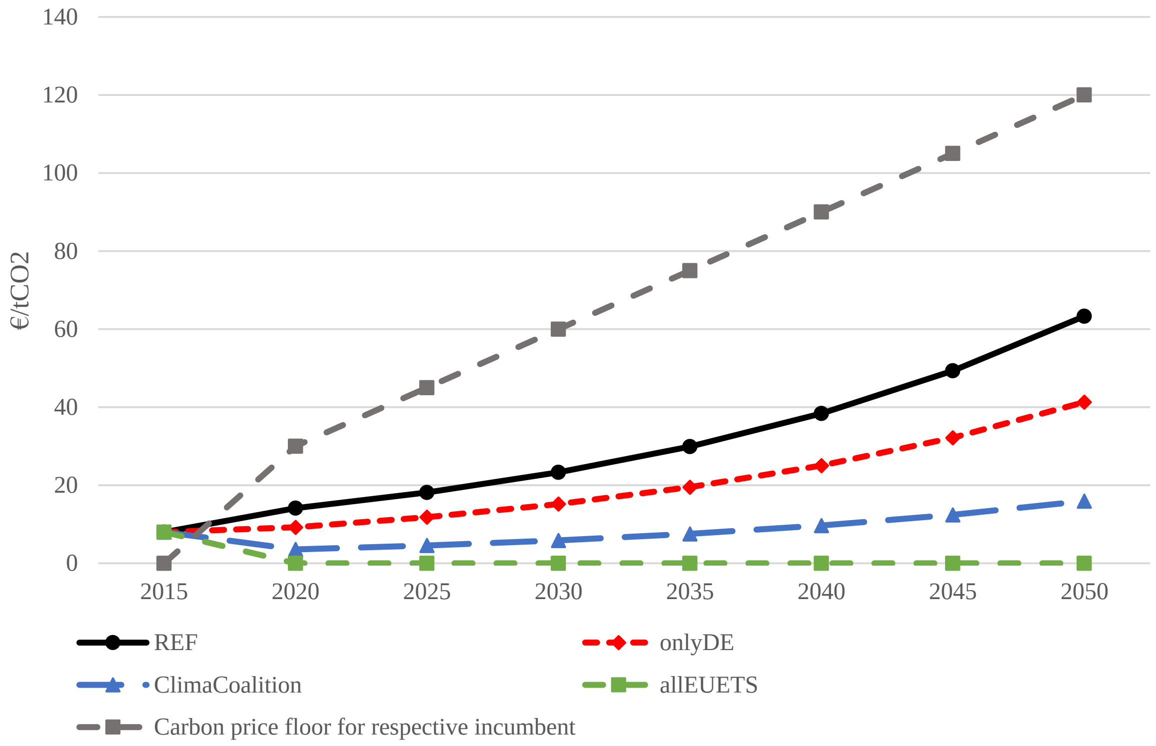



*Figure 2. Evolution of ETS prices as different coalitions of countries implement a carbon price floor.*

Figure 3(a) shows that higher effective carbon prices in neighbouring countries (as in *ClimaCoalition* and *allEUETS)* reduce the decreasing effect of the carbon price floor on coal generation in Germany in 2020, compared to *onlyDE*. Beyond 2030, the higher neighbouring prices have little influence on German coal use. However, German coal-based generation remains considerably lower than in *REF*, at a level of 108 to 144 TWh/yr in 2020 (*REF*: 192 TWh/yr) and a level of around 50 TWh/yr in 2030 (*REF*: 143 TWh/yr). The higher levels of German coal generation in *ClimaCoalition* and *allEUETS*, compared to *onlyDE,* is due to higher marginal coal costs in other members of the coalition. This allows German coal-based generation to remain competitive. Still, as in *onlyDE*, Germany becomes a net importer in *ClimaCoalition* and *allEUETS* from 2020 onward: while there is a neutral exchange balance by 2020 in *REF*, net imports lie between 37 and 86 TWh/yr in *allEUETS* and *onlyDE*, respectively. Figure 3(b) shows that emissions are slightly below 100 $MtCO_2$ in 2030 in all coalition scenarios, i.e., the emission targets are achieved. To illustrate in more detail the forces driving the emissions reduction, in Appendix G we show the generation-mix changes in these scenarios.

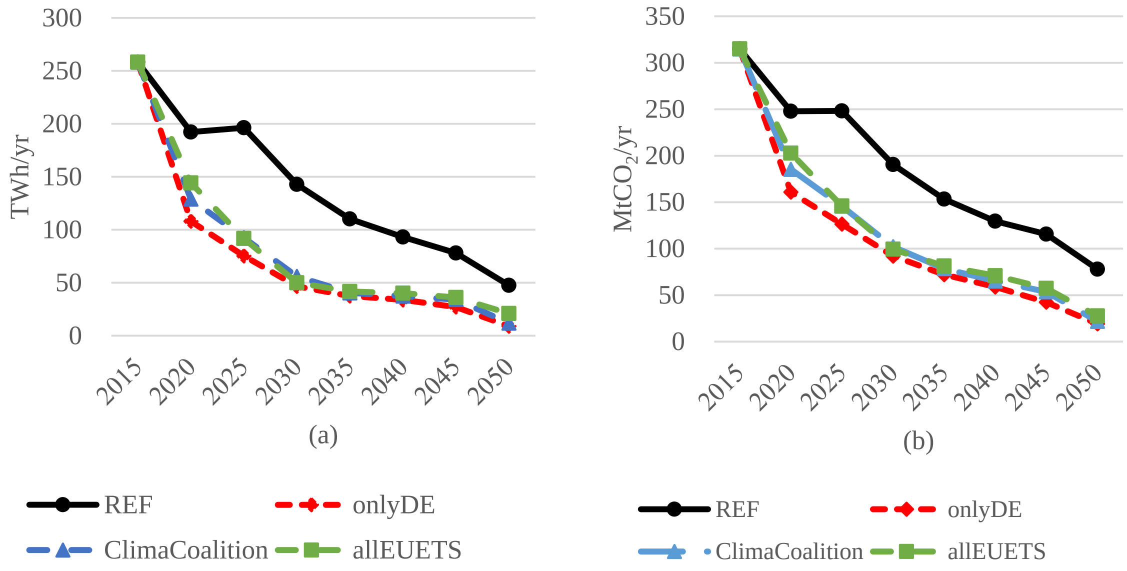



*Figure 3. Evolution of (a: left panel) coal-based generation and (b: right panel) emissions from electricity generation in Germany in different policy scenarios.*

From previous figures, it is clear that if Germany applies the default carbon price floor, it would reach the targets, independently of whether other countries implement it. We made additional runs to investigate the exact carbon price floor required for Germany to meet its 2030 targets. We assumed that either the coalition or the entire EU ETS would also implement this price, thereby differing from *onlyDE*, in which other countries only see the ETS price. The prices are only slightly higher than for *onlyDE* (33 €/t$CO_2$): 35 €/t$CO_2$ for *ClimaCoalition* and 37 €/t$CO_2$ for *allEUETS*. When the coalition implements the carbon price floor, the resulting carbon price support equals 19 €/t$CO_2$.

### 4.4. Estimating the waterbed effect

When Germany or the coalition applies the 'default' path (30 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050) the resulting (lower) ETS prices encourage fossil-based generation in countries not belonging to the coalition (waterbed effect in space) and lead to an increase of total EU ETS emissions in the long-term (waterbed effect in time). Figure 4 shows that emissions in EU ETS countries in *onlyDE* and *ClimaCoalition* are lower than in *REF* in the medium-term (until 2030). Hence, emission reductions in Germany and other coalition countries also have an EU-wide effect, due to additional $CO_2$ prices above 30 €/t$CO_2$. However, in the long-term the effect reverses, leading to higher total emissions by 2035 in *onlyDE* and *ClimaCoalition*.

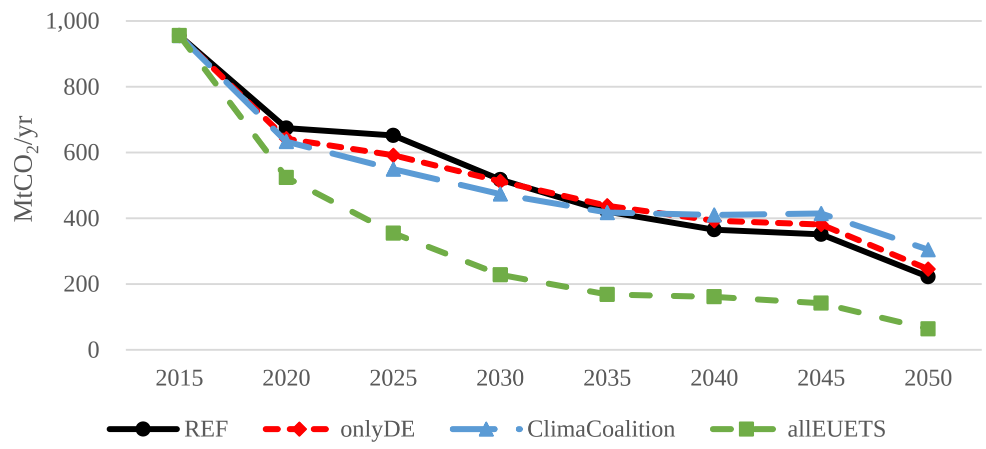



*Figure 4. Evolution of emissions from electricity generation in the EU ETS under different policy scenarios.*

To illustrate this carbon leakage, we compare coal generation in coalition and non-coalition countries in *REF* and *ClimaCoalition* (see Figure 5). In *REF*, no one implements a carbon price floor, whereas coalition members do so in *ClimaCoalition*. If coal-based generation in coalition members (solid lines) in *REF* (black) is compared with *ClimaCoalition* (blue), there is a substantial decrease of ~170 TWh/yr in 2025. This reduction is partially offset (~50 TWh) by an increase in coal-based generation in the other countries (dashed lines) – mainly Poland, Czech Republic, and Greece - from *REF* (black) to *ClimaCoalition* (blue), representing the waterbed effect in space. The total EU-wide change is shown in red bars. Until 2030, the net change is negative, i.e., EU-wide coal-based generation is reduced by $CO_2$ carbon price support in the coalition. After 2030, the red bars turn positive, i.e., coal-based generation increases across the EU through the implementation of a carbon price floor in the coalition. This demonstrates the waterbed effect in "time".

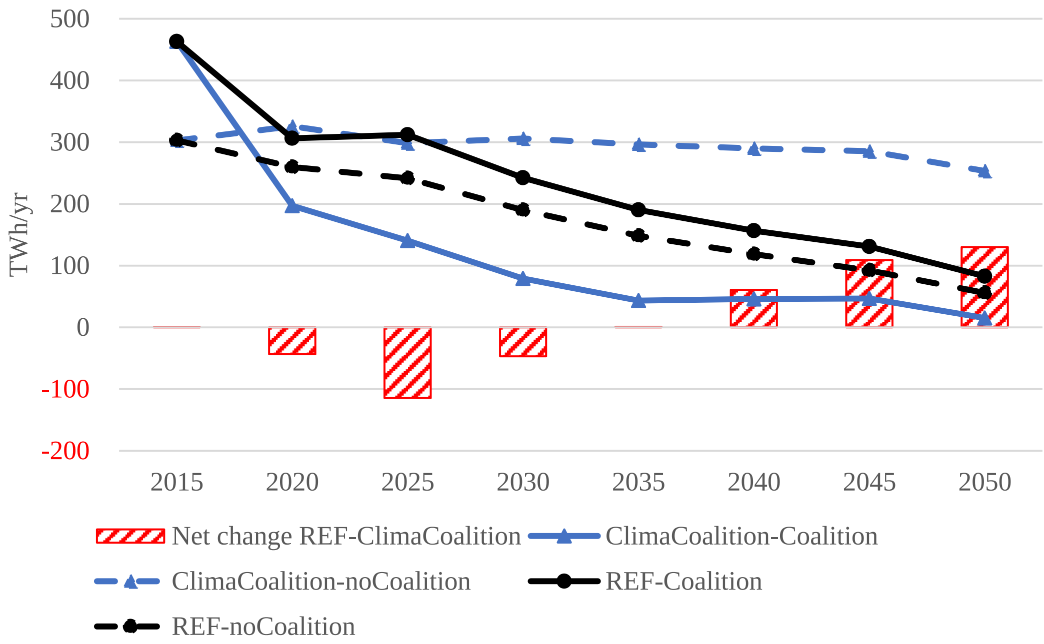



*Figure 5. Comparison of coal-based generation in coalition and non-coalition countries in REF and ClimaCoalition.*

If the ETS emission cap remains unchanged until 2050, the emission reductions in the medium-term, caused by the implementation of a carbon price floor in a sub-group of countries, would be completely offset in the long-term without the MSR. Figure 6 shows the cumulated emissions from 2018 to 2032 and 2052 in the EU ETS under different coalitions without the MSR (as each time-step in LIMES-EU accounts for five years, 2050 accounts for the period 2048-2052). Emissions until 2032 (blue) are 0.5 $GtCO_2$, 0.9 $GtCO_2$ and 3.7 $GtCO_2$ lower in *onlyDE*, *ClimaCoalition* and *allEUETS* respectively than in *REF*. As Germany reduces its 2018-2032 emissions by 1.4 GtCO2 in *onlyDE*, a waterbed effect of (1.4 $GtCO_2$-0.5 $GtCO_2$)/1.4 $GtCO_2$ = 64% in that period is observed. In *ClimaCoalition*, the waterbed effect is reduced to (1.7 $GtCO_2$ – 0.9 $GtCO_2$)/1.7 $GtCO_2$ = 50%.

However, cumulated emissions until 2052 (black) equal those of *REF* (16.0 $GtCO_2$) in all scenarios but *allEUETS*. In the long-term, there is thus a full waterbed effect in *onlyDE* and *ClimaCoalition*. Only when all the EU ETS members implement the carbon price floor (*allEUETS*), there is no waterbed effect and cumulated emissions until 2052 decrease by 7.8

$GtCO_2$ (~50%). This reduction of 2018-2052 emissions materialises in *allEUETS* because the price floor is sufficiently high such that the ETS cap is no longer binding (recall Figure 2).

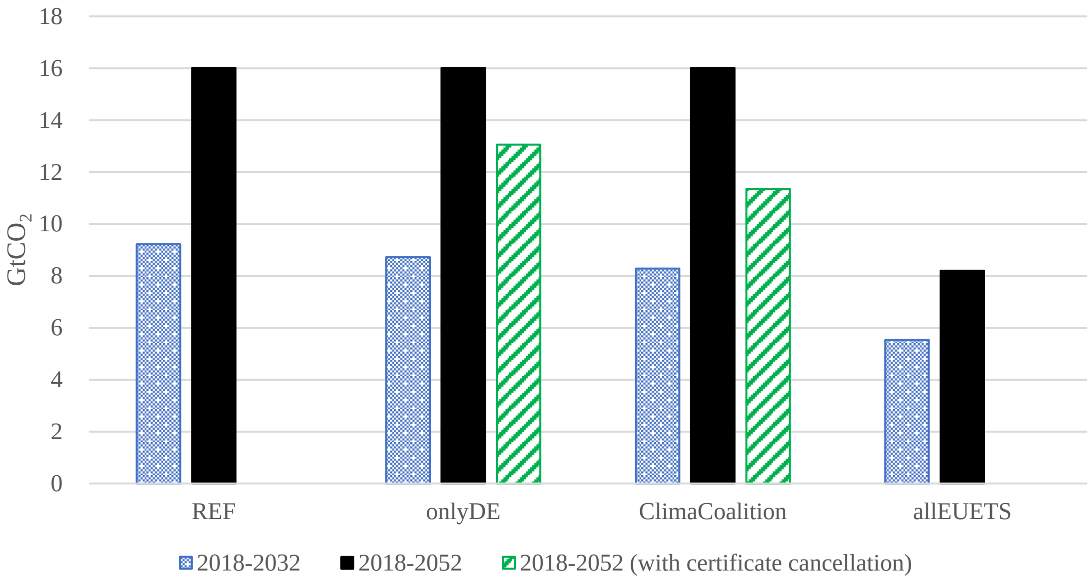



*Figure 6. Cumulated emissions from electricity generation in the medium and long-term (without the MSR). Green bars show long-term emissions with the cancellation of certificates by countries implementing a carbon price floor (onlyDE_c/ ClimaCoalition_c).*

A proposed solution to avoid the waterbed effect is to cancel certificates. A legal provision for doing so was included in the reformed ETS Directive[13], but the exact implementation details are yet to be defined. We quantify the number of certificates that would need to be cancelled to ensure that additional actions by individual states would be completely effective at the EU ETS level. For a country to completely preserve its efforts in the long-term, i.e., avoid the waterbed effect, it would have to cancel certificates equivalent to the additional reductions triggered by the implementation of the carbon price floor. The cancellation path is thus estimated as the difference between emissions of countries implementing a carbon price floor in the reference scenario (*REF*) and the scenarios with a carbon price floor (*onlyDE* and *ClimaCoalition*). For example, when only the EU ETS (*REF*) is implemented German's emissions are 191 MtCO2

[13] Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814. OJ L 76, 19.3.2018, p. 3–27.

in 2030. If only Germany implements the carbon price floor (*onlyDE*), its emissions are 92 MtCO2 in the same year. Hence, Germany would need to cancel certificates equalling 99 MtCO2. We follow the same procedure for the remaining years for both scenarios involving just a part of the EU members implementing such a measure and aggregate the yearly required cancellations for the entire time horizon. As a larger coalition reduces more emissions, more certificates would need to be cancelled: in *onlyDE*, 3.0 $GtCO_2$ need to be cancelled, while in *ClimaCoalition* this figure increases to 4.6 $GtCO_2$. Figure 6 shows the cumulative 2018-2052 emissions from scenarios in which certificates are cancelled in green bars. Cancellation leads to a reduced carbon budget, from 16.0 $GtCO_2$ to 13.1 $GtCO_2$ in *onlyDE_c* and to 11.4 $GtCO_2$ in *ClimaCoalition_c*. Since such cancellation affects the public finances of the engaged countries, its implementation is unlikely, even for a coalition. Besides, the EU members are confident that the MSR could be enough to limit the waterbed effect. The MSR reform provides for automatic cancellation from 2023 onward. Is this sufficient to prevent the waterbed effect? We evaluate this in the next section.

### 4.5. Effect of the MSR

The most relevant factor determining the number of certificates cancelled through the MSR is the total number of allowances in circulation (TNAC) at any year. For details of how the MSR works, see Appendix H. Importantly, the TNAC itself depends on the price of certificates: the lower the price, the higher emissions, and in turn the lower the TNAC and, by extension, cancellations. Accordingly, since the coal phase-out ceteris paribus reduces demand for certificates and thus the price, cancellation is reduced. At the same time, there is emission leakage to other countries which increases the demand for certificates and thus counteracts the effect on cancellation (Perino et al., 2019). These two effects and respective sizes thus determine the overall impact of the MSR.

Burtraw et al. (2018) provide the MSR simulation tool we use to asses ex-post cancellation up to 2030 (end of EU ETS Phase IV). We find that this automatic cancellation is only partially successful in preventing the waterbed effect. It should be acknowledged that using this tool comes with two limitations: (*a*) it only allows us to evaluate the impact of the MSR until 2030. In light of the uncertainty about the MSR mechanism in the long-term, – a revision is due in 2021 already – we think this can be justified. In particular, all data suggests cancellation will be highest in the coming decade because of the high TNAC. (*b*) The tool does not allow us to determine the interaction effect between prices and cancellations, which would require an endogenous representation of the MSR in LIMES-EU that is beyond the scope of the paper. We nevertheless think that the ex-post assessment is a good approximation, and leave confirmation to further research.

We estimate the waterbed effect by comparing MSR cancellations under the baseline emissions of *REF*, (equal to 3117 Mt$CO_2$ – see Table 5, the sum of row "baseline cancellation"), with the cancellations in the scenario *onlyDE*, in which only Germany implements a carbon floor price. While annual emissions in Germany decrease by 1339 Mt$CO_2$ between 2018 and 2030 (see Figure 3), the total reduction at the EU ETS-level adds up to only 480 Mt$CO_2$ in the same period (see Figure 4 and Table 5, row "Additional reductions"). In other words, there is a 64% waterbed effect until 2030. As the MSR only reacts to EU ETS wide emissions, the total MSR cancellation only increases to 3392 Mt$CO_2$, a difference of 275 Mt$CO_2$ to the baseline cancellations in *REF*, thereby reducing the waterbed effect until 2030 to 44%. If Germany wanted to prevent the waterbed effect over the full time horizon (until 2052) and prevent banking of freed-up certificates for later time periods, it would have to cancel certificates amounting to 1064 $MtCO_2$ (=1339 – 275 $MtCO_2$), otherwise the waterbed effect would only be reduced from 100% to 91%[14] in the long-term.

We also simulated the MSR until 2030 for the scenario *ClimaCoalition*. In this scenario, climate coalition members reduce their emissions by 1716 $MtCO_2$ between 2018 and 2030, but the total reduction at the EU ETS-level adds up only to 850 $MtCO_2$ in the same period. In other words, there is a 50% waterbed effect until 2030. This leads to an MSR cancellation of 3536 $MtCO_2$: 420 $MtCO_2$ are cancelled on top of those in the baseline scenario, reducing the waterbed effect until 2030 from 50% to 26%. This reduction implies that coalition members would need to voluntarily cancel certificates for 1296 $MtCO_2$ (=1716 – 420 $MtCO_2$) to avoid the waterbed effect until 2030. The MSR would only take care of 24% of the total. In the long term, the additional 420 $MtCO_2$ cancelled through the MSR implies a reduction in the full waterbed effect from 100% to 91% (1 – 420/4666).

[14] 0.91 = 1 - 275/2955, where 2955 $MtCO_2$ is the amount of certificates that would need to be cancelled to avoid the full waterbed effect in the long-term.

*Table 5. Simulation of MSR when Germany implements a carbon price floor (data in $MtCO_2$). Source: Burtraw et al. (2018); own calculations.*

| | | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | SUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Summarised results from Burtraw et al. (2018) | | | | | | | | | | | | | | | |
| Planned allowance supply | | 1,787 | 1,756 | 1,824 | 1,739 | 1,933 | 1,695 | 1,740 | 1,613 | 1,547 | 1,520 | 1,493 | 1,466 | 1,431 | |
| Planned auction | | 960 | 960 | 1,100 | 973 | 945 | 918 | 890 | 862 | 835 | 807 | 779 | 752 | 724 | |
| Realised auction | | | 544 | 767 | 675 | 699 | 657 | 775 | 743 | 717 | 698 | 676 | 652 | 724 | |
| Emissions | | 1,754 | 1,684 | 1,639 | 1,656 | 1,627 | 1,565 | 1,590 | 1,501 | 1,501 | 1,464 | 1,414 | 1,370 | 1,269 | |
| TNAC | 1,700 | 1,733 | 1,389 | 1,241 | 1,026 | 1,086 | 956 | 991 | 984 | 912 | 858 | 834 | 830 | 992 | |
| Intake into MSR | | 0 | 416 | 333 | 298 | 246 | 261 | 115 | 119 | 118 | 109 | 103 | 100 | 0 | |
| Extra intake [a] | | | 250 | 1,300 | | | | | | | | | | | |
| Cancellation | | 0 | 0 | 0 | 0 | 0 | 2,144 | 303 | 0 | 147 | 145 | 128 | 124 | 125 | 3,117 |
| MSR level | | 0 | 666 | 2,299 | 2,597 | 2,843 | 960 | 772 | 891 | 861 | 826 | 801 | 776 | 652 | |
| Simulation-based on LIMES-EU results – scenario in which Germany implements a carbon floor price (*onlyDE*) | | | | | | | | | | | | | | | |
| Realised auction | | | 536 | 753 | 657 | 677 | 633 | 759 | 722 | 690 | 667 | 642 | 621 | 597 | |
| Additional reductions [b] | | 32 | 32 | 32 | 32 | 32 | 60 | 60 | 60 | 60 | 60 | 5 | 5 | 5 | 480 |
| Resulting emissions | | 1,722 | 1,652 | 1,607 | 1,623 | 1,595 | 1,504 | 1,530 | 1,441 | 1,440 | 1,404 | 1,409 | 1,365 | 1,264 | |
| TNAC | 1,700 | 1,765 | 1,446 | 1,316 | 1,116 | 1,186 | 1,093 | 1,172 | 1,203 | 1,165 | 1,142 | 1,089 | 1,060 | 1,100 | |
| Intake into MSR | | 0 | 424 | 347 | 316 | 268 | 285 | 131 | 141 | 144 | 140 | 137 | 131 | 127 | |
| Extra intake | | | 250 | 1,300 | | | | | | | | | | | |
| Cancellation | | 0 | 0 | 0 | 0 | 0 | 2,227 | 329 | 5 | 178 | 176 | 163 | 162 | 152 | 3,392 |
| MSR level | | 0 | 674 | 2,321 | 2,637 | 2,904 | 962 | 764 | 899 | 866 | 830 | 804 | 773 | 748 | |
| Simulation-based on LIMES-EU results – scenario in which the 'Climate Coalition' implements a carbon floor price (*ClimaCoalition*) | | | | | | | | | | | | | | | |
| Realised auction | | | 534 | 749 | 652 | 672 | 626 | 751 | 710 | 675 | 649 | 621 | 598 | 572 | |
| Additional reductions [c] | | 41 | 41 | 41 | 41 | 41 | 103 | 103 | 103 | 103 | 103 | 44 | 44 | 44 | 850 |
| Resulting emissions | | 1,713 | 1,643 | 1,598 | 1,615 | 1,586 | 1,462 | 1,488 | 1,399 | 1,398 | 1,362 | 1,370 | 1,326 | 1,226 | |
| TNAC | 1,700 | 1,774 | 1,461 | 1,337 | 1,140 | 1,214 | 1,155 | 1,269 | 1,331 | 1,320 | 1,320 | 1,285 | 1,271 | 1,324 | |
| Intake into MSR | | 0 | 426 | 351 | 321 | 274 | 291 | 139 | 152 | 160 | 158 | 158 | 154 | 152 | |
| Extra intake | | | 250 | 1,300 | | | | | | | | | | | |
| Cancellation | | 0 | 0 | 0 | 0 | 0 | 2,249 | 337 | 14 | 194 | 195 | 185 | 186 | 178 | 3,536 |
| MSR level | | 0 | 676 | 2,326 | 2,647 | 2,921 | 963 | 765 | 904 | 870 | 833 | 807 | 775 | 750 | |

[a] The extra intake corresponds to backloading certificates and certificates not allocated until the end of phase 3, therefore they are not accounted in the planned auctions.

[b] Corresponding to the difference between EU ETS emissions in *REF* and *onlyDE*.

[c] Corresponding to the difference between EU ETS emissions in *REF and ClimaCoalition*.

### 4.6. Limitations and further work

Our results show how different groups of countries implementing a carbon price floor influence market dynamics. Although we study the impact of different coalitions, we acknowledge that coalitions might change over 30 years. Coalition formation is a dynamic process in which members join based on market and political reasons. One might expect, for instance, that the largest economies initially implement a carbon price floor, and that political pressure (and hopefully the right incentives) will lead other countries to join. This dynamic is one of the limitations of our framework. Alternative approaches are needed to analyse the interplay between countries and to determine the conditions under which other countries might join.

Another limitation of our work is related to the evolution of the emission cap. Our results are sensitive to the assumed share of emissions accounted for by industry within the EU ETS. This highlights the varying dynamics in electricity generation, dependant on the decarbonisation of energy-intensive industry. In further research, we intend to capture the interaction between industry and heating and the electricity sectors and its impact on the decarbonisation pathway in more detail. The interaction with non-ETS sectors (e.g., transport) should also be analysed in detail, as the electrification of these sectors will lead to increased electricity demand, thereby increasing pressure in the EU ETS.

Finally, further research is needed to endogenise the MSR in a capacity-expansion and dispatch model.

## 5. CONCLUSION & DISCUSSION

Germany set up the "Coal Commission" to propose measures that would enable the country to phase out coal, and in turn to reach its 2030 climate target. According to our results, the suggested CPO path would narrowly miss the 2030 emission target. One of the measures considered to reach the target is a carbon price floor for electricity generation that would reduce additional emissions to the EU ETS, thus filling the "price gap". We analysed two key aspects and related risks for implementing such a carbon price floor: the price level necessary to reach the German 2030 climate target, and the size of the waterbed effect that would arise from such a national carbon price support under the EU-wide emission cap.

Our results show that an effective $CO_2$ price of around 34 €/t$CO_2$ would be needed to reach the 2030 targets under default assumptions. For this, a national carbon price support of around 13 €/t$CO_2$ would be required. However, it would be risky for Germany to set a fixed price support at exactly 13€/t$CO_2$ as the appropriate level fluctuates, depending on several factors. First, if other countries implement a similar carbon price floor, the competitiveness of German coal-fired plants would be favourable, causing their production to increase, requiring a higher carbon price. The evolution of key power sector parameters also impacts the appropriate price level, particularly the expansion of cross-border transmission that could limit imports of relatively cheap renewable electricity. Accordingly, to ensure that the 2030 level will be reached with certainty, even under (very extreme and unlikely) unfavourable conditions, a carbon price floor of around 87 €/t$CO_2$ would be required. If, however, conditions turn out to be favourable, a price of only 17 €/t$CO_2$ would be needed. To avoid both over- and undershoot, the level could be set to adapt over time and in response to how market conditions unfold.

We also investigate policy interaction and related risks with the EU ETS caused by the waterbed effect "in space" and "in time" when Germany or a coalition of countries takes additional action. Keeping in mind the cumulated emissions until 2030, we find that the implementation of a stringent carbon price floor would reduce German emissions by around 1339 Mt$CO_2$ until 2030, while emissions in neighbouring countries would go up by 860 Mt$CO_2$, implying a 64% waterbed effect without MSR. An ex-post estimate shows that the MSR would cancel about

275 $MtCO_2$, reducing the waterbed effect until 2030 to 44%. If more countries were to implement such a carbon floor price, the waterbed effect until 2030 would be reduced from 64% to 50% without MSR. More certificates would be cancelled through the MSR (420 $MtCO_2$), further reducing the waterbed effect until 2030 to 26%. As a result, less unilateral cancellation would be needed. A coalition of countries can, therefore, reduce emissions, at least in the medium-term. As also proposed by the Coal Commission, the German government could cancel allowances to further reduce emissions, effectively neutralising the waterbed effect.

In the long-term (until 2050), if the ETS cap for the trading periods between 2030 and 2050 is not tightened, these reductions are almost completely offset. The waterbed effect would occur to almost a full extent even when the coalition is large (91%), underscoring the limitations of automatic MSR cancellations in the long term. Whether or not the full waterbed effect materialises depends on crucial future reforms that may further tighten the caps for the trading periods 2030-2040 and 2040-2050 in response to additional national actions. At the same time, it must be noted that the cancellation provision of the 2018 ETS reform is subject to review in 2021, and may become ineffective. This underlines the considerable regulatory uncertainty around the interaction of national policies with the EU ETS and makes a strong case for implementing price floors and sequencing national action to the EU level.

Is it then advisable for Germany to implement such a carbon price floor? Strengthening the ETS and pursuing an EU-wide approach should clearly be the preferred choice. Under the current political situation in many member states, this might take years or even decades – too long to ensure that the 2030 target is reached. A carbon price floor has the advantage of being easily implemented – by a country or group of countries – and of aligning with the EU ETS, at least, when allowances are cancelled such that its integrity is not undermined. Cancelling allowances is instrumental for sending a strong message that the EU ETS will continue to play an important role and that European climate policy will not renationalise. The discussion on carbon price floors could eventually be taken to the EU-level.

## 6. APPENDIX

### A. The EU ETS reform

The EU's parliament and council in 2017 eventually agreed to reform the ETS, which will take effect in the 4th phase (from 2021 to 2030) (European Council, 2017a). These reforms are comprised of an increase of the linear reduction factor (2.2% annually compared to the 1.74% in the 3rd phase) setting the annual cap and a revision of the previously agreed upon Market Stability Reserve (MSR) (European Union, 2015) with the aim of reducing the current market surplus of around 1.6 $GtCO_2$ of allowances (EEA, 2017a). The MSR was originally created with an amendment of the Directive 2003/87/EC (European Commission, 2015a) and will start operating in 2019: 900 million 'backloaded allowances' will be placed on the MSR (instead of being auctioned in 2019-2020) and the unallocated allowances will be transferred to the MSR in 2020 (European Council, 2017b). The recent revision establishes the thresholds to determine the amount of certificates that will be transferred to the MSR (intake) or from the MSR (outtake) from/to the market via auctions. From 2023 on, the number of allowances in the MSR exceeding the number of allowances auctioned the previous year will be cancelled. This provision could compensate the effects of uncoordinated national measures and thus avoid the waterbed effect, at least partially (Burtraw et al., 2018; Graichen and Matthes, 2018; Perino, 2018)[15]. In addition, the new ETS Directive 2018/410 entails that "Member States should have the possibility of

[15] For details of the reform, see: http://www.consilium.europa.eu/en/press/press-releases/2017/11/22/reform-of-the-eu-emissions-trading-system-council-endorses-deal-with-european-parliament/

cancelling allowances from their auction volume in the event of closures of electricity-generation capacity in their territory"[16].

B. Model data sources

We use data from publicly available sources to calibrate and run our model. Demand is taken from the EU reference scenario (European Commission, 2016a) for EU members and SFOE (2013) for Switzerland. Final demand for Norway and the Balkans is estimated by scaling demand in 2010 according to their neighbouring countries' demand growth rates. Initial capacities are set exogenously. The existing capacities of generation and storage technologies, as well as their age structure, are derived from Platts (2011), Eurostat (2018) and the Open Power System Data (2018); in specific cases, data from national ministries, e.g., BMWi (2018) is used. Capacity data in 2020 used as fixed (for conventional sources) or as lower bounds (for vRES) is taken from ENTSO-E (2017a). Cross-border transmission capacities for 2010 is taken from ENTSO-E (2010) and for 2015 from ACER/CEER (2017). For 2025 and 2030, cross-border transmission capacities (used as benchmark in the model) is taken from the TYNDP 2016 (ENTSO-E, 2015).

Capital costs and fuel costs are taken from the REMIND model[17]. For calibration purposes, we estimate nuclear availability factors per country in 2015 using generation data from ENTSO-E (2017b), but for the remaining years, a constant availability factor is assumed for all countries. Except for hydro and vRES, the annual availability of generation technologies is equal for all model regions. Hydropower availability factors are estimated from IRENA (2017) data and were assumed to remain constant for the entire simulation. For vRES, data from IRENA (2017) is also used to estimate annual availability factors for existing facilities (capacity built until 2015 in the model). Newly installed capacity has higher availability factors. For this, we use

[16] see http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=EN
[17] For REMIND, detailed harmonized model documentation is available at the Common IAM documentation, https://www.iamcdocumentation.eu/Model_Documentation_-_REMIND.

data from NREL (2013) for wind and Pietzcker et al. (2014) for PV. This accounts for the improvements in efficiencies and the trend toward lower turbine-to-rotor ratios for wind. Technologies “waste” and “other gases” are only considered for Germany. Their availability and emission factors are calculated based on 2015 generation (BMWi, 2016). We consider transmission losses equal to 8% and a rate of autoconsumption for each technology from Agora (2014) to better account for gross demand in the long-term in scenarios with a high share of vRES.

As mentioned in Section 3.1, to capture hourly and seasonal variations, we use a cluster algorithm to estimate representative times slices of demand and vRES availability. We use ENTSO-E (2016) data for the historic electricity demand levels and historical weather data from the ERA-Interim dataset (Dee et al., 2011) for the vRES infeed. Table B1 summarises the main parameters used for each technology.

Two additional parameters require a more detailed estimation. These are the electricity-only cap used to model the EU ETS and the electricity-only target for Germany in 2030. Its computation is described as follows.

*Estimation of an electricity-only cap within the EU ETS*

The current EU ETS comprises two main sectors: aviation and the stationary sector (energy industries). The latter comprises electricity and heating production, and industry (e.g., petroleum refining). Aviation was included in the ETS[18] in 2012, but the extent of its coverage changed between 2012 and 2016. This sector has a cap (set at 210 Mt$CO_2$ for each year between 2013-2020[19]), but in the event of a shortage, airlines are allowed to buy allowances from the

[18] Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community. O.J. L 8, 13.1.2009, p. 3–21.
[19] Decision of the EEA joint committee No 93/2011 of 20 July 2011. Available at https://ec.europa.eu/clima/sites/clima/files/ets/allowances/aviation/docs/eea_20072011_en.pdf

stationary sector (EEA, 2016). The cap for the stationary sector was set at 2084 $MtCO_2$ in 2013, after which it decreases at a rate of 1.74% per year until 2020. For the period 2021-2030 ($4^{th}$ trading phase of the EU ETS), the cap decreases at a rate of 2.2% per year to achieve a 43% reduction of emissions with respect to 2005 (EEA, 2016). Although a decreasing rate beyond 2030 is not set yet, emissions are expected to drop 80-95% by 2050 with respect to 2005 (European Commission, 2016b); we assume a reduction of 90%. For the calculation of an electricity-only cap, we used only the stationary sector cap despite the allowance for the aviation sector to buy allowances from this sector. We assumed that the aviation cap would be set after 2020 according to the decarbonisation possibilities in this sector.

The challenge of estimating an electricity-only cap lies in assessing the emission path of the heating and industry sectors. As Figure B1 shows, emissions from the combustion of fuels decreased from 1461 $MtCO_2$ in 2005 to 1181 $MtCO_2$ in 2015 (EEA, 2018). Using the energy balances from Eurostat (2017) and the emission factors from the IPCC's guidelines (Gomez et al., 2006) for the period 2005-2015, we estimated electricity- and heating-related emissions: 940 $MtCO_2$ and 223 $MtCO_2$ in 2015, respectively. Emissions from other industries accounted for 639 $MtCO_2$. To reflect current ETS scope, industries' share in the total verified emissions remained around 35% during the same period. Given the difficulty of decarbonising such industries (Krey et al., 2014; Luderer et al., 2018), we assume that the share of these industries would increase linearly to 55% in 2050. We also assume that the share of heating remains constant (12%) until 2050. There is an additional 4% of verified emissions from combustion that remain unallocated between heating and electricity production. They might correspond to emissions from plants with an erroneous code within the EU ETS. We also assume this share to remain constant over time. Hence, the share of non-electricity-related emissions increases from 51% in 2020 to 71% in 2030. The resulting electricity-only cap is thus estimated to decrease from 896 $MtCO_2$ in 2020 to 76 $MtCO_2$ in 2050.

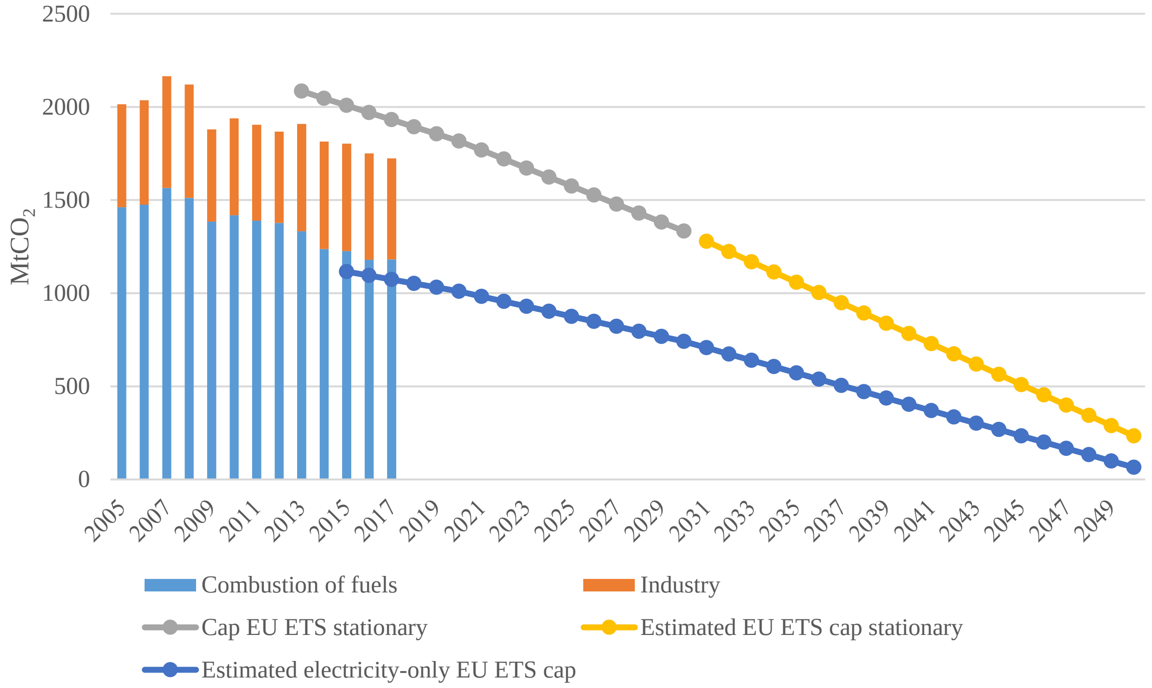



*Figure B1. Evolution of historical emissions and estimation of the future overall EU ETS cap and electricity-only cap within the EU ETS. Data sources: EEA (2017b, 2016); own calculations.*

*Estimation of an electricity-only 2030 target in Germany*

The Climate action plan (BMUB, 2016) sets the emissions target for the energy conversion sector at 175-183 $MtCO_2$-eq (equivalent to 61-62% reduction) with respect to 1990 (466 $MtCO_2$-eq), as well as a weaker target of 49-51% reductions for the industry sector, which also encompasses power generation in industry power plants. Based on this, we derive a target for electricity-related power generation emissions. The mentioned target depends on the attribution of emissions for CHP plants and the emission reductions in the rest of the energy supply sector. All emissions attributable to electricity generation (after deducting heat-related emissions from CHP plants) were 366.9 $MtCO_2$ in 1990 (Harthan and Hermann, 2018). This amount includes the electricity emissions produced by industrial facilities, which, as mentioned above, have a different target in 2030. Industry electricity generation emissions were 33.9 $MtCO_2$ in 1990

(Harthan and Hermann, 2018). Hence, deducting the 33.9 $MtCO_2$ of industrial emissions gives 333 $MtCO_2$ for "energy conversion" - electricity emissions, i.e., the electricity-related emissions produced by public power plants in 1990. Assuming a 50% reduction target for the industry results in 17 $MtCO_2$ in 2030. Assuming a reduction of 61% for the public power plants implies that these emissions should be cut to 130 $MtCO_2$. Therefore, the carbon emissions only for power (w/o heat portion of CHP) should add up to 147 $MtCO_2$.

*Table B1. Main parameters used to model the operation of technologies in LIMES-EU.*

| **Technology** | **Lifetime (yr)** | **Build time (yr)** | **Investment costs (2010€/kW)** [e] | **Efficiency** [f] | **Hourly availability** | **Annual availability** | **Fixed O&M costs (factor of inv. Costs per yr)** | **Variable costs (€/MWh)** | **Emission factor (GtC/ZJth)** | **Auto-consumption** | **Ramping** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nuclear | 60 | 3.1 | 7000 | 0.33 | 1 | 0.9 | 0.03 | 5 | 0.0 | 0.05 | 0 |
| Hard coal | 45 | 2.2 | 1800 | 0.38-0.5 | 1 | 0.8 | 0.02 | 6 | 26.3 | 0.08 | 0.35 |
| Hard coal with CCS | 45 | 2.2 | 3475->2600 | 0.43 | 1 | 0.8 | 0.02 | 29 | 2.6 | 0.08 | 0.35 |
| Lignite coal | 55 | 2.2 | 2100 | 0.36-0.47 | 1 | 0.8 | 0.02 | 9 | 29.2 | 0.08 | 0.25 |
| Lignite with CCS | 55 | 2.2 | 3475->2600 | 0.42 | 1 | 0.8 | 0.02 | 34.3 | 2.9 | 0.08 | 0.25 |
| Natural gas combined cycle | 45 | 1.3 | 900 | 0.54-0.6 | 1 | 0.8 | 0.03 | 4 | 15.2 | 0.03 | 0.5 |
| Natural gas combined cycle with CCS | 45 | 1.3 | 1942->1450 | 0.52 | 1 | 0.8 | 0.03 | 18 | 1.5 | 0.03 | 0.5 |
| Natural gas turbine | 45 | 0.5 | 400 | 0.41 | 1 | 0.8 | 0.03 | 3 | 15.2 | 0.03 | 1 |
| Hydropower | 80 | 1.8 | 2500 | 1 | [a] | [c] | 0.02 | 0 | 0.0 | 0.02 | 1 |
| Biomass | 45 | 1.3 | 2000 | 0.42 | 1 | 0.8 | 0.04 | 6 | 0.0 | 0.05 | 0.35 |
| Wind onshore | 25 | 0.8 | 1291->1150 | 1 | [b] | [c] | 0.03 | 0 | 0.0 | 0 | -- |
| Wind offshore | 25 | 1.2 | 4073->2829 | 1 | [b] | [c] | 0.05 | 0 | 0.0 | 0 | -- |
| PV | 25 | 0.5 | 950->500 | 1 | [b] | [c] | 0.01 | 0 | 0.0 | 0 | -- |
| Concentrated solar | 30 | 1.0 | 4760->3560 | 1 | [b] | [c] | 0.03 | 0 | 0.0 | 0 | -- |
| Pumped-storage | 80 | 1.8 | 1500 | 0.8 | [d] | [d] | 0.01 | 0 | 0.0 | 0 | -- |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen electrolysis | 20 | 0.5 | 1620->820 | 0.7 | [d] | [d] | 0.02 | 3 | 0.0 | 0 | -- |
| Oil | 40 | 1.3 | 400 | 0.42 | 1 | 0.8 | 0.04 | 3 | 22.0 | 0.09 | 1 |
| Hydrogen combined cycle | 40 | 1.3 | 1170 | 0.58 | 1 | 0.8 | 0.03 | 4 | 0.0 | 0.03 | 1 |
| Hydrogen combustion turbine | 40 | 0.5 | 520 | 0.33 | 1 | 0.8 | 0.04 | 3 | 0.0 | 0.03 | 1 |
| Hydrogen fuel cell | 40 | 0.5 | 1600->700 | 0.45 | 1 | 0.8 | 0.02 | 3 | 0.0 | 0.03 | 1 |
| Waste incineration | 40 | 1.3 | 2000 | 0.22 | 1 | 0.8 | 0.04 | 3 | 42.0 | 0.2 | 0.35 |
| Other fossil-based plants, e.g., coke gas | 40 | 1.3 | 900 | 0.76 | 1 | 0.8 | 0.03 | 3 | 55.3 | 0.08 | 0.5 |
| Li-ion batteries | 20 | 1.8 | 1343->735 | 0.8 | [d] | [d] | 0.01 | 0 | 0.0 | 0 | -- |

[a] Country-dependent availability (based on 2010-2015 generation and capacities)

[b] Country and hourly-dependent availability

[c] Dependent on hourly availabilities

[d] Dependent on energy input (endogenous variable)

[e] For those technologies with two values, the first corresponds to the investment costs in 2020 and the second to those in 2050

[f] For those technologies with two values, they correspond to the range of efficiencies depending on the time the plant was built

## C. Iterative approach to estimating a national/regional carbon price floor in an LP model

Fell et al. (2012) formulated a model to provide insight into different ways to implement a carbon price, e.g., price floors and ceilings. Firms maximise their profits (resulting revenues from buying and selling emission are certificated) subject to a certificates trading constraint in a cap-and-trade system, i.e., they are allowed to bank and borrow certificates. The Fell et al. (2012) formulation allows one to ensure a carbon price floor for a group of countries sharing the same cap-and-trade constraint (in this case, the EU ETS). The authors show, through the first-order condition for optimality, that the selling price equals the Lagrange multiplier on the banking/borrowing constraint. To increase the allowance price, the firm buys back certificates from the market. This nonetheless affects the market price, which is the same for all firms. Adapting this formulation to LIMES-EU would not allow us to analyse different countries implementing a carbon price floor. It only allows an analysis of all EU ETS members implementing such a policy.

To cope with this limitation, we implemented an iterative process (see Figure C1). The economic intuition behind this process is: when a country or coalition implements a carbon price floor, the ETS price, or more generally, the resulting carbon price from a cap-wide mechanism involving a larger group of countries, will decrease. This occurs because the demand for certificates decrease. There is thus a need to adjust the carbon price support to reach the desired carbon price floor.

In a first iteration ($i=1$) the model is run without exogenous carbon price support ($x_{t,c,i}$), i.e., as in our reference scenario. The carbon price is computed from the emissions constraint (Eq. (C.1)), i.e., the carbon price ($P_{t,i}$) is the Lagrange multiplier of the state equation of the allowances bank $v\_bank_t$, where $p\_elcap_t$ is the electricity-only emission cap (estimated in Appendix B) and $v\_emi_{t2}$ is the volume of emissions at the EU ETS level.

$$v\_bank_t = v\_bank_{t-1} + p\_elcap_t - v\_emi_{t2} \quad \text{(C.1)}$$

If $P_{t,i}$ is lower than the desired carbon price floor ($P^*_{t,c}$) for every country *c* and time *t*, the model is run again. In the next iteration, we assume an exogenous $CO_2$ price, i.e., the needed carbon price support ($x_{t,c,i}$), equivalent to the difference between the desired carbon price floor ($P^*_{t,c}$) and $P_{t,i}$ (see Figure C2). From the results of this new iteration ($i + 1$), we estimate $P_{t,i+1}$, and the resulting effective carbon price (carbon price support, $x_{t,c,i}$, plus the ETS price, $P_{t,i+1}$). If the effective carbon price is not within the tolerance interval ($P^*_{t,c}(1 \pm tol)$), a new iteration is needed. In each iteration, we update the carbon price support. The parameter $tol$ is set to 1%.

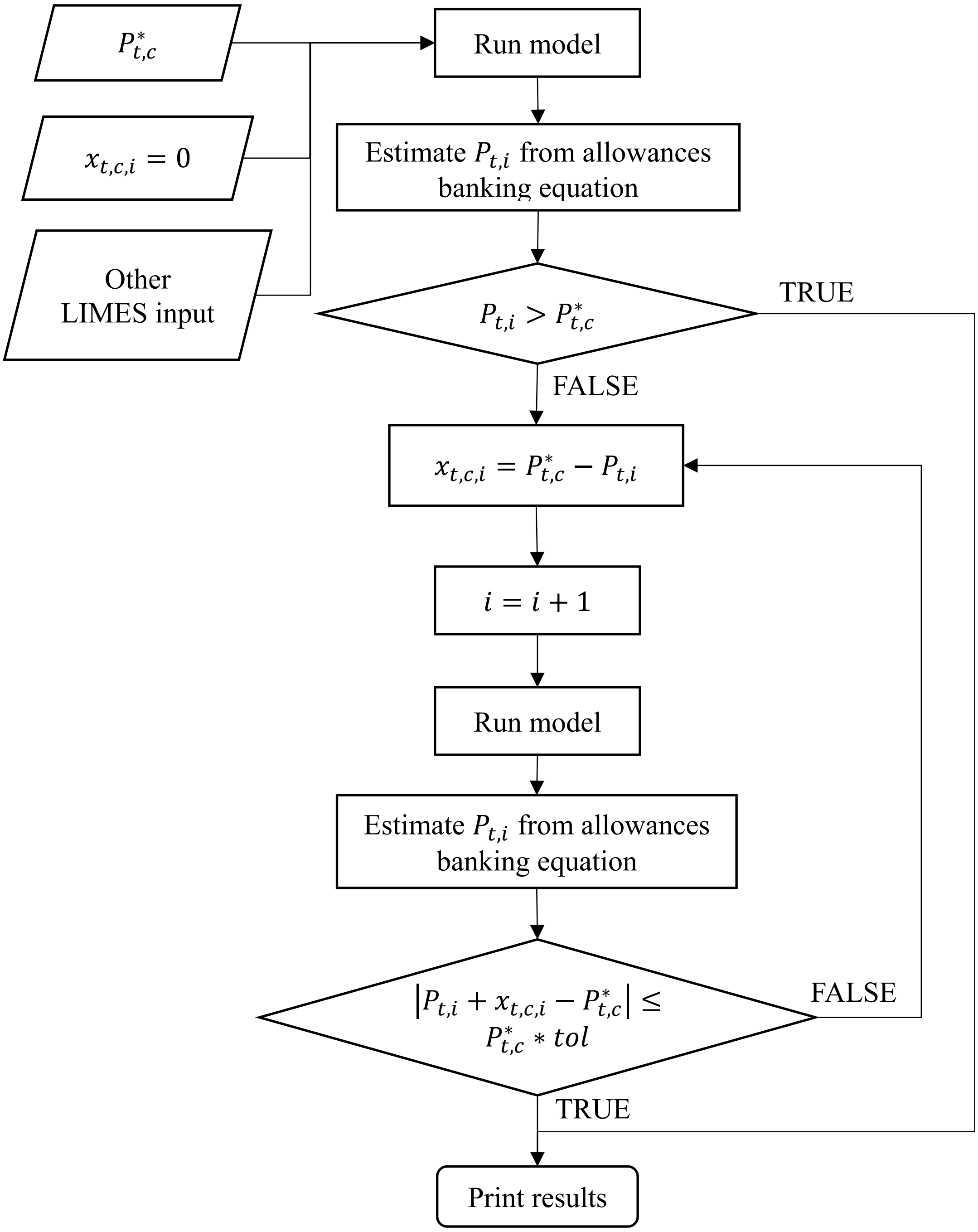



*Figure C1. Flow diagram explaining the iterative process used to run the model when a carbon price floor was implemented.*

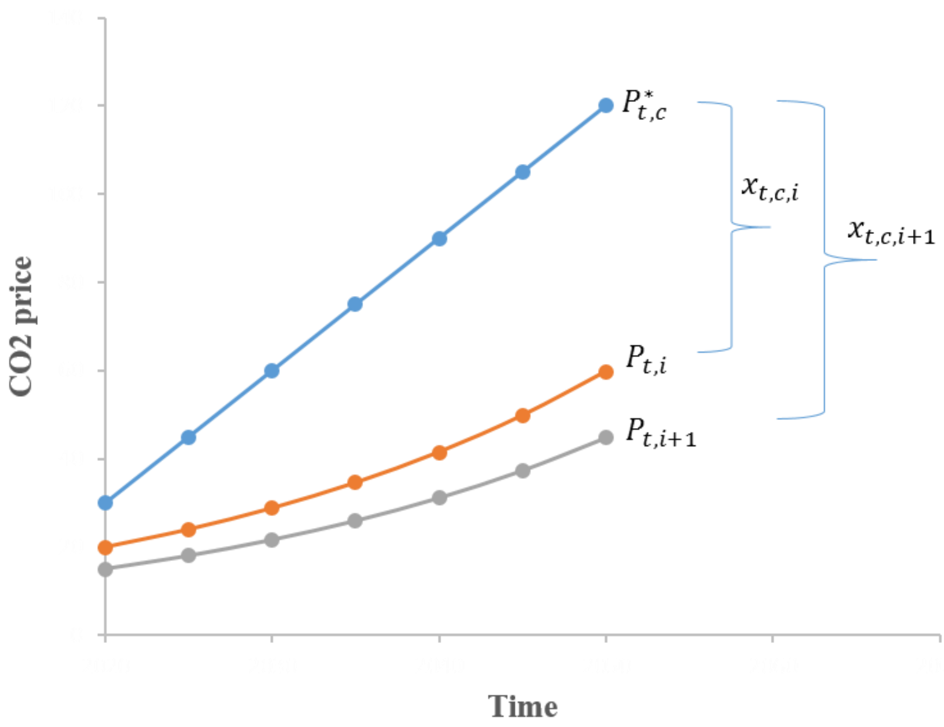



*Figure C2. Carbon price support adjustment between two iterations, for countries implementing a carbon price floor.*

D. Model vs reality (base-year dispatch)

For the base year 2015, only the dispatch of generation, storage, and transmission technologies is optimised by LIMES-EU. The installed capacities are given exogenously. We compare the dispatch resulting from LIMES-EU with historic electricity production data from ENTSO-E (2017b) (given the lack of fossil-based generation data for the Netherlands, we use data from Mantzos *et al.* (2018)). In addition, we compare the modelled carbon emissions with historical emissions[20] in 2015. To replicate the historic dispatch, we assume an exogenous $CO_2$ price of 8 €/t$CO_2$, which is consistent with the average price for EU ETS allowances in this year.

[20] To estimate the electricity-related emissions, we allocate the emissions from CHP according to the share of their gross electricity output in their total output (heat and electricity) using data for the EU from Mantzos *et al.* (2018). Due to the lack of data, for Norway, Switzerland and Balkan we use emissions from public electricity and heat production from IEA (2017b).

Figure D1 shows both historical emissions and model results for 2015. Despite the simplifying model assumptions, model results appropriately fit historical emissions. Only model results for France show a large deviation from historic data. The reason for this deviation can be explained by Figure D2, which gives the historic and model-based electricity generation mix of each region and the EU28 Member States in total. In reality, the electricity mix of France varies slightly to the model. A small share of electricity provided by hard coal and natural gas-fired power plants in reality, while in the model nuclear reaches a higher generation. This is because there is only a simplified representation of CHP for Germany in the model, while in the other countries no additional revenues for heat from CHP plants are represented. Accordingly, we underestimate their dispatch. As most of french generation is emission-free, this underestimation leads to a sizable relative error between the modelled and historical results. However, these have little impact on EU ETs emissions as French emissions represent a very small portion of the EU ETS. For Germany, we also present the historical emissions from a national source, the Öko Institute (Harthan and Hermann, 2018), which is in charge of reporting on the national emissions. This value is closer to our modelled results.

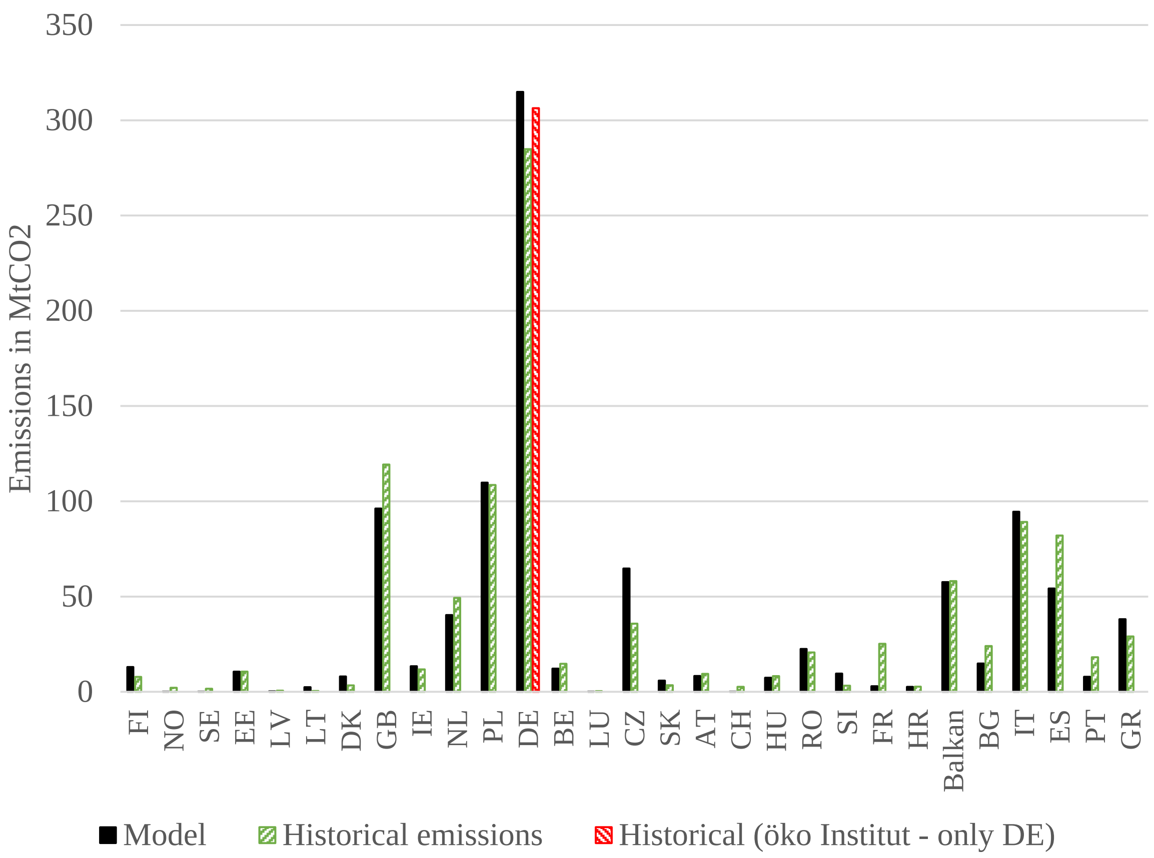



*Figure D1. Comparison of historical and modelled region-specific CO2 emissions in 2015. Source: Mantzos et al. (2018), IEA (2017b), Harthan and Hermann (2018); own calculations and model results.*

Other regional electricity mixes deviate from historical data, e. g., hard coal is overrated in Italy and underrated in Poland. This is because the model abstracts from regional differences in prices for primary energy sources as well as taxes and charges. It optimises the overall European electricity system, without taking into account market failures that might distort the cost-efficient outcome in reality. This certainly is a drawback when aiming at reproducing historic market outcomes, but it is reasonable to derive benchmarks for the cost-efficient future development of the European electricity system. Meanwhile, the aggregated electricity mix of the EU28 is well reproduced by the model. Only lignite is somewhat overrated, while biomass and vRES generation are lower than in reality.

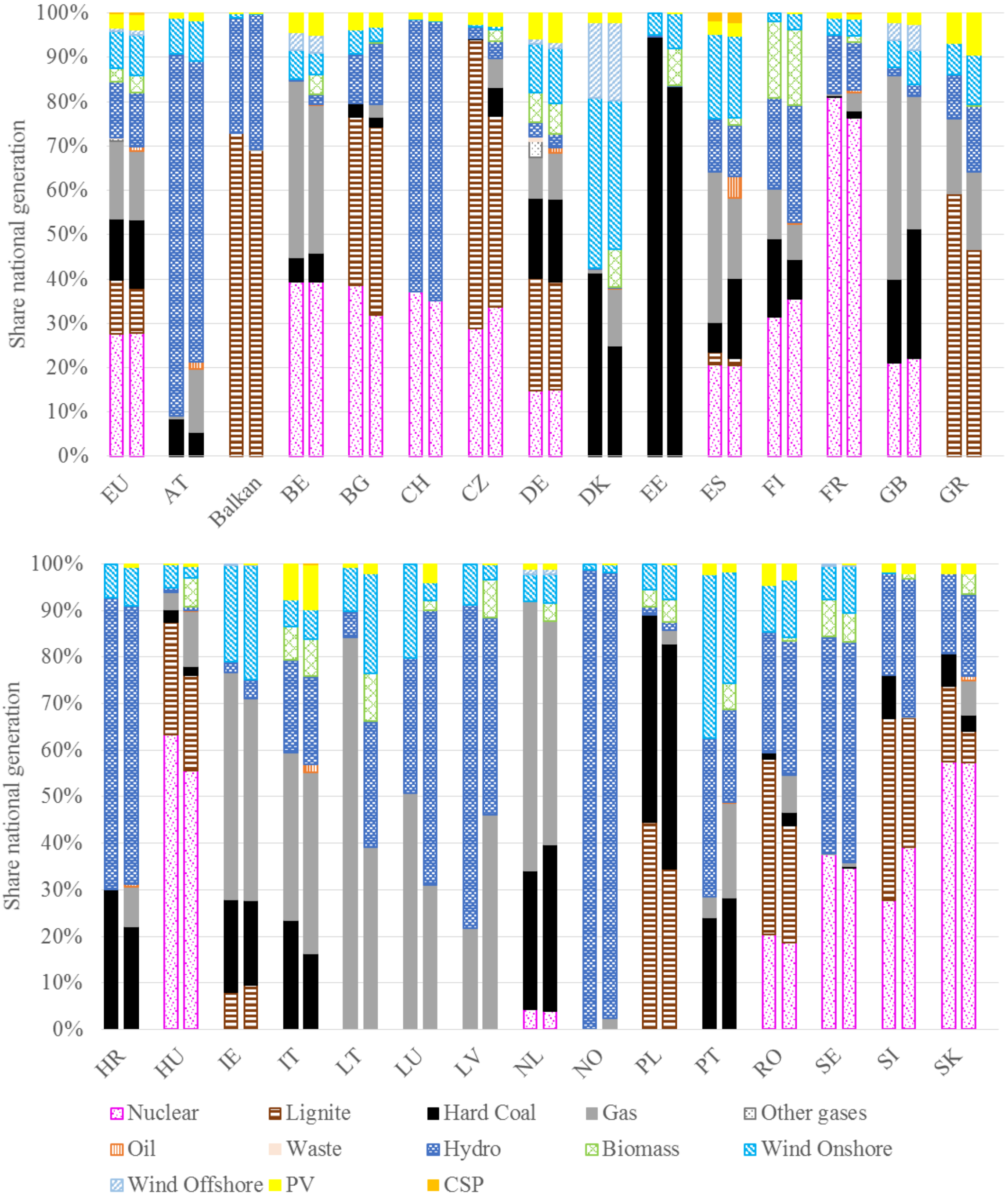



*Figure D2. Comparison of the model-derived (left bar) and the historic (right bar) region-specific electricity generation mix in 2015. Source: ENTSO-E (2017b); own model results.*

## E. Complementary sensitivity analysis

*Policy and economic parameters*

The following analysis is performed based on *REF* assumptions, i.e., there is only an emissions cap-and-trade system, and there is no country implementing a carbon price floor. We apply the same variations as those used to estimate the range of price that Germany would need to implement to reach the 2030 target (see Table 4). To evaluate the impact of high and low fuel prices, we use price ranges from the *Sustainable development* and *Current policies* scenarios of the WEO (IEA, 2017a) (see Table E1). Oil, gas and hard coal prices are provided for 2025 and 2040, which we inter/extrapolate for the full time horizon. Since the high coal prices provided by the WEO are slightly lower than our *REF* scenario, and given recent market dynamics (coal prices are currently around 70-100$/t (2.8-4 $/GJ) (MarketWatch, 2018), so WEO prices seem to be low), we assume high coal prices were 30% higher than in our *REF* scenario.

*Table E1. Fuel prices used for the sensitivity analysis and comparison with REF assumptions (€/GJ). Source: IEA (2017a); own calculations.*

| | | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Coal | Low | 2.3 | 2.1 | 2.3 | 2.3 | 2.2 | 2.2 | 2.2 | 2.1 |
| | *REF* | 2.3 | 3.0 | 3.0 | 3.0 | 3.1 | 3.2 | 3.4 | 3.6 |
| | High | 2.3 | 2.3 | 2.8 | 2.9 | 3.1 | 3.2 | 3.4 | 3.6 |
| Gas | Low | 5.3 | 5.8 | 6.6 | 6.9 | 7.2 | 7.5 | 7.8 | 8.1 |
| | *REF* | 5.3 | 6.2 | 6.8 | 7.1 | 7.8 | 8.3 | 8.4 | 8.9 |
| | High | 5.3 | 6.3 | 7.8 | 8.5 | 9.2 | 9.9 | 10.7 | 11.4 |
| Oil | Low | 8.0 | 11.0 | 12.3 | 11.8 | 11.4 | 10.9 | 10.5 | 10.0 |
| | *REF* | 8.0 | 11.9 | 13.2 | 14.3 | 16.4 | 16.0 | 17.6 | 19.3 |
| | High | 8.0 | 13.2 | 16.5 | 18.8 | 21.0 | 23.2 | 25.4 | 27.6 |

Additionally, we evaluate the impact of the potential changes in the EU ETS due to Brexit and the carbon price in Balkan countries. For the UK we evaluate two scenarios: (*a*) the UK does not belong to the EU ETS after 2022 (we subtract 11% from the EU ETS cap afterwards) and applies a carbon price increasing from of 20 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050; (*b*) the UK remains in the EU ETS and applies a carbon price floor of 20 €/t$CO_2$ in 2020, increasing linearly to 120 €/t$CO_2$ in 2050. For Balkan, we evaluate two scenarios: (*a*) Balkan countries do not apply any carbon price; (*b*) Balkan implements a carbon price equivalent to the EU ETS (without belonging to it).

Table E2 summarises the impact of the changes in individual variables on prices and generation-mix at the EU ETS level. ETS prices are 24% lower (higher) when the cap is higher (lower), which mainly affects coal generation. Our results are more sensitive to high than low fuel prices. ETS prices are 23% lower when fuel prices are high and 20% higher when fuel prices are low. This implies that a higher (lower) $CO_2$ price is needed to decarbonise the system when fuel prices are low (high). With high prices, coal generation is less affected due to the loss of competitiveness of gas-fired plants. When fuel prices are low, coal-based generation slightly decreases and gas-based generation increases in the long-term. When fuel prices are high, coal-based generation increases and gas-based generation decreases considerably.

When vRES costs are high (low), carbon prices increase (decrease) by 27% (38%). As expected, their deployment is inversely proportional to their costs, displacing mainly gas when the costs are low due to the low carbon prices. When transmission capacity remains constant, carbon prices increase by 26%, mainly affecting coal generation. Interestingly, gas generation increases considerably despite the higher emission costs, which is explained by the wind generation being locked-in.

Largest changes occur when varying the discount factor. Carbon prices decrease by 50% when the discount factor is 2.5% and increase by 122% when it is 15%. A high discount rate works in favour of gas generation over coal generation as there is a sharper decrease in emissions. At the same time, the higher discount rate leads to lower vRES generation in both 2030 and 2050. When demand increases, carbon prices increase by 32%, leading to more gas and vRES generation. Despite the higher consumption requirements, the increased demand for certificates leads to lower coal generation, which is being replaced by gas.

Finally, when the UK leaves the EU and implements a price increasing from 20 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050, ETS prices increase by 10%. The higher emissions costs in the UK encourages exports from the EU ETS, and thus increases the demand for EUA. If the UK remains in the EU and implements (alone) a carbon price floor increasing from 20 €/t$CO_2$ in 2020 to 120 €/t$CO_2$ in 2050, carbon prices decrease by 7%. This is the same effect as when Germany or a coalition implement a carbon price floor: demand for certificates decrease, and thus ETS prices. Still, overall coal generation decreases because the drop of generation in the UK is larger than the increase (waterbed effect) in the rest of EU ETS members.

The assumption regarding Balkan prices has little effect on our results. When Balkan implements a price equal to the ETS, carbon prices increase in the EU ETS because fossil-based plants are encouraged to produce more to export to Balkan countries. On the contrary, when Balkan does not implement a carbon price, ETS prices slightly decrease because there is higher availability of (cheap) imports from Balkan fossil-based plants.

*Table E2. Summary of sensitivity analysis.*

| Scenario | | Price 2050 (€/t$CO_2$) | Generation (TWh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Coal | | Gas | | Solar | | Wind | |
| | | | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 | 2030 | 2050 |
| Reference | | 63 | 432 | 138 | 263 | 243 | 325 | 1206 | 1107 | 1740 |
| Emission cap | High | 49 | 492 | 169 | 267 | 263 | 316 | 1180 | 1074 | 1699 |
| | Low | 78 | 367 | 94 | 258 | 222 | 326 | 1214 | 1154 | 1811 |
| Fossil fuel prices | Low | 76 | 425 | 126 | 260 | 276 | 319 | 1209 | 1104 | 1766 |
| | High | 49 | 466 | 183 | 206 | 152 | 316 | 1218 | 1095 | 1836 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Low gas /high coal | 66 | 472 | 163 | 191 | 112 | 318 | 1219 | 1102 | 1880 |
| | High gas /low coal | 53 | 392 | 117 | 325 | 362 | 314 | 1190 | 1080 | 1667 |
| vRES capital costs | Cheap | 39 | 436 | 156 | 193 | 154 | 350 | 1174 | 1275 | 1924 |
| | Expensive | 80 | 436 | 95 | 340 | 338 | 298 | 1184 | 999 | 1666 |
| Constant transmission | | 80 | 382 | 86 | 395 | 390 | 333 | 1292 | 1077 | 1609 |
| Discount rate | 2.5% | 31 | 410 | 216 | 200 | 203 | 330 | 1215 | 1172 | 1727 |
| | 7.5% | 115 | 461 | 50 | 352 | 185 | 301 | 1205 | 1005 | 1797 |
| | 10% | 131 | 474 | 33 | 425 | 140 | 282 | 1171 | 940 | 1659 |
| | 12.5% | 134 | 481 | 31 | 503 | 141 | 263 | 1126 | 867 | 1579 |
| | 15% | 140 | 458 | 25 | 590 | 155 | 234 | 1099 | 820 | 1551 |
| High electricity demand | | 83 | 351 | 82 | 304 | 449 | 367 | 1740 | 1241 | 2567 |
| UK | Out and CPF of 20->120* | 69 | 372 | 111 | 231 | 201 | 306 | 1175 | 911 | 1366 |
| | In EU ETS and CPF of 20->120 | 59 | 443 | 135 | 255 | 213 | 319 | 1201 | 1109 | 1793 |
| Balkan | No CP | 63 | 430 | 141 | 262 | 241 | 322 | 1180 | 1104 | 1755 |
| | CP = ETS | 66 | 421 | 136 | 277 | 246 | 329 | 1174 | 1128 | 1819 |

*The generation values in these scenarios are not perfectly comparable to the Reference scenarios because they do not account for UK generation.

Finally, we run a scenario in which CCS is available (as of 2030). Changes in results are negligible: investments in these technologies are just 0.4 GW in lignite in Poland in 2050, producing 2 TWh/yr.

*Modelling parameters*

We evaluate the impact of parameters that are not directly related to technical, regulatory or economic constraints, but rather to modelling decisions of two kinds: (*a*) helping the calibration and making the model results more realistic, and (*b*) reducing the computational cost while still providing suitable results. The former refers mainly to two parameters: the capacity margin (10%) and the transmission losses (8%). The latter refers to the number of representative days used to model each model year (6 days, i.e., 48 time slices).

We use a capacity margin of 10%, as this is in line with values from TSOs used in the past – the derated margins in Spain and Poland were 10 and 9% (ENTSO-E, 2017c), while the margin applied to underrated capacities in several US markets is ~14%-17% (EIA, 2012). To test how much a different choice would impact results, we do two extreme variations: setting the margin to 0, and increasing it to 20%. The capacity margin has little impact on carbon prices (< 1%). They do nonetheless have a significant impact on gas investments: generation capacity is up to 20% lower when the margin is 0%, and up to 15% higher when the margin is 20%. Still, impact on electricity prices is little. The internal transmission/distribution losses parameter does have an impact on carbon prices: these are 13% higher (lower) when losses are 13% (3%).

We run the model with up to 45 representative days (i.e., 360 time slices per year). We show the variables related to the German target (emissions and carbon prices in Germany in 2030 – see Figure E1) and, on a more general level, those that could be affected by the short-term impact of more/less renewables due to the higher model granularity (wind, solar, gas and coal generation in Germany and the EU ETS – see Figure E2). The results from our default configuration (6 days) tend to converge to those of the largest configuration (45 days). We focus on the results for 2030. Emissions at the EU ETS and the german level are within a range of ±5%. Carbon prices in a configuration of 6 days are 1% lower than in the one with 45 days, but

~10% lower than the maximum reached (30 days). The lower granularity smooths the vRES profiles, so it is easier to accommodate their output, i.e., electricity systems are easier to decarbonise. This is highlighted by the variation in generation outputs for wind, solar, coal and gas. The output patterns vary strongly –even non-monotonically- when less than five days are used. With fewer representative days, wind generation is higher, affecting mainly to gas and solar generation. Indeed, largest variations occur for gas generation at the EU ETS level (generation is 20% lower with six days than with 16 days). Still, the difference between the output with six and the highest resolution (45 days) is never higher than 15%.

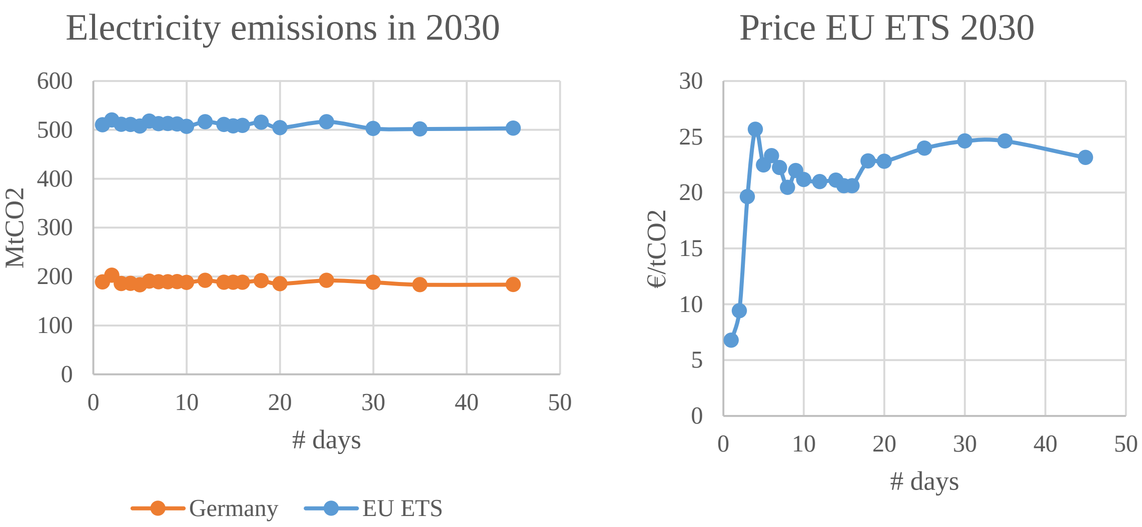
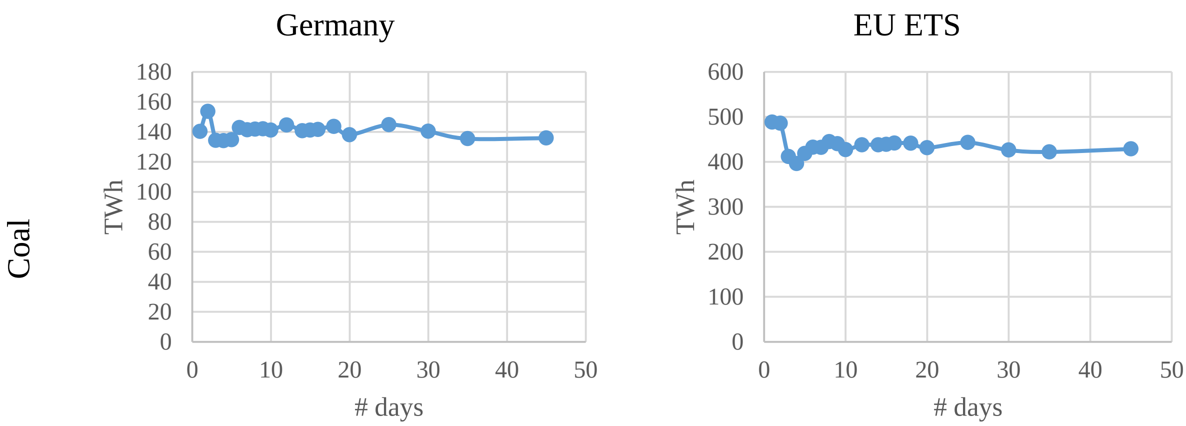



*Figure E1. Impact of modelled representative days on emissions and carbon prices in Germany in 2030.*



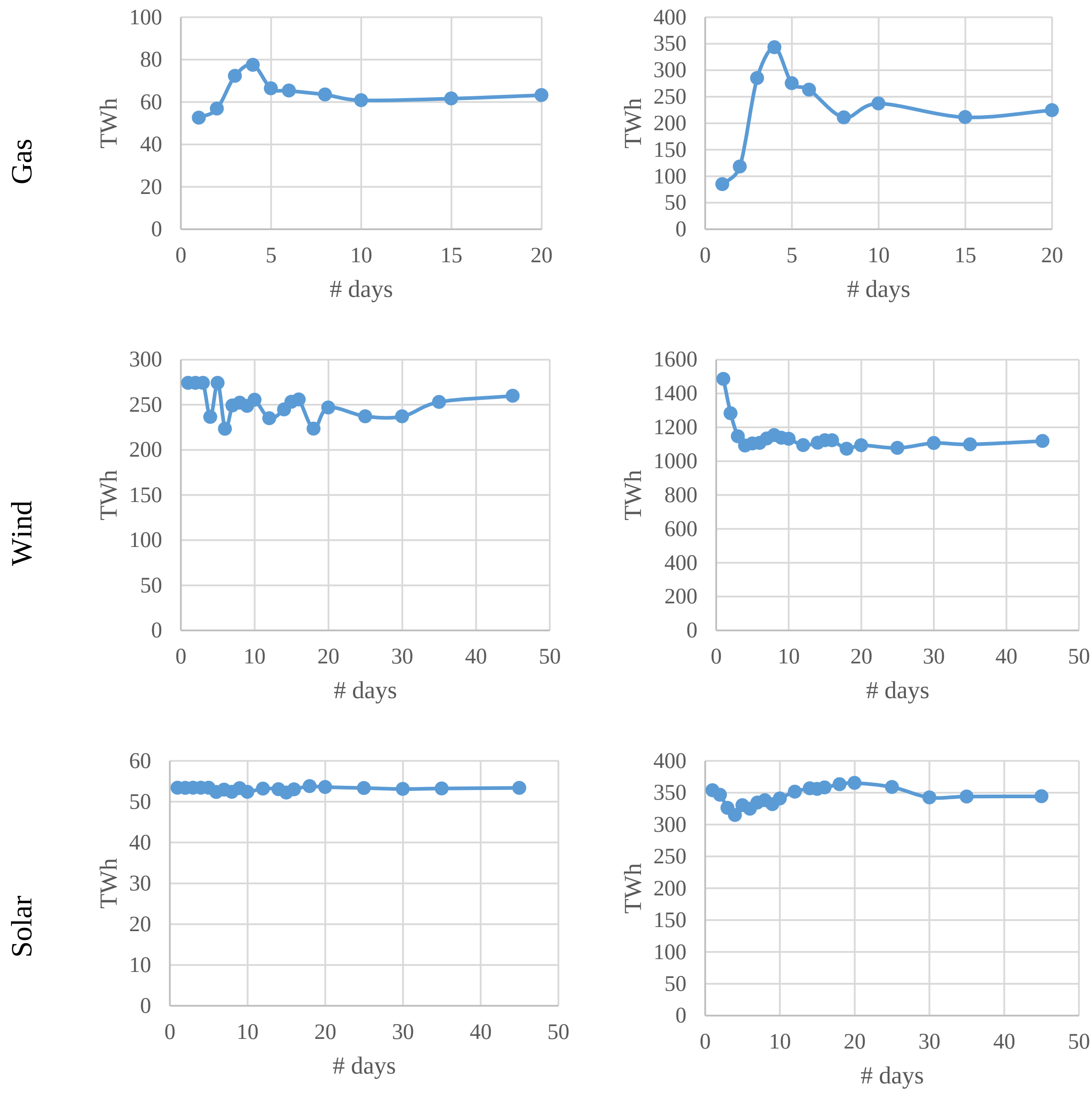



*Figure E2. Impact of modelled representative days on generation volumes in Germany and the EU ETS.*

## F. Comparison with existing literature

We compare the results for our estimated carbon price floor for Germany to reach its 2030 emission reduction target in the electricity system. Only two studies estimate the required price for Germany to reach its target. Huneke and Perez Linkenheil (2016) estimate a price between 50 and 75 €/t$CO_2$ (a graphical interpolation would result in a price of ~60 €/t$CO_2$), the price for the rest of EU ETS being 27.6 €/t$CO_2$. Although such a price remains within the range estimated through our sensitivity analysis, it is difficult to assess which particular parameters yield the differences as there is little information about the model used by the authors (Power2Sim). From Hermann et al. (2017), the price would be 47 €/t$CO_2$, 37 €/t$CO_2$ being the EU ETS price. Note that the difference in prices (10 €/t$CO_2$) is very similar to our estimated value (13 €/t$CO_2$). This is important because the difference drives coal-based imports from abroad. One of the reasons for such a difference are considered fuel prices. Their gas price is roughly 15% higher, while the hard coal is 10% lower, making fuel substitution more difficult. In addition, renewable and nuclear capacities abroad are lower than in LIMES, and demand in these countries about 20% higher than in LIMES, which favours even more coal profitability, and thus making the required carbon price higher. The data used in this model correspond to Scenario B and Vision 3 of the Ten Year Network Development Plan 2014 (ENTSO-E, 2014), in which demand growth is considered to be rather optimistic and capacities of fossil-based technologies conservative (near 2015 values).

In a recent study, Matthes et al. (2019) analyse the decommissioning pathway suggested by the Coal Commission. They also assume a RES target of 65% for 2030 and a carbon price of 27 €/t$CO_2$, under the assumption that certificates are cancelled by Germany to ensure that the carbon price path equals that of their reference scenario, i.e., waterbed effect in space is strongly limited. Although the Coal Commission has proposed the cancellation of certificates, the trade-offs from a financial point of view could discourage such a measure. This effect is not negligible: according to our results, the price in *REF* is 23 €/t$CO_2$ by 2030, while this is 19 €/t$CO_2$ in *CPO_RESbase*. Under such conditions: 65% target and regulated CPO, we estimate that Germany would require a carbon price floor of 27 €/t$CO_2$. This is nonetheless under the assumption that only Germany implements it. It is thus difficult to compare their result to ours. Based on additional LIMES runs, the EU ETS carbon price required would be 30 €/t$CO_2$, just slightly higher than Matthes et al. (2019)'s estimation. One of the reasons for such a difference is the electricity demand, which is ~10% higher in our model.

## G. Long-term evolution of the generation-mix

Figure G1 and Figure G2 show the generation mix in 2015, 2030 and 2050 for the main scenarios evaluated in the model (*REF*, *onlyDE*, *ClimaCoalition* and *allEUETS*) in Germany and the EU ETS, respectively. The 2015 values are presented to provide insights on the magnitude of the transformation faced by electricity systems in the long-term.

Due to the increasing carbon prices (whether or not a carbon price floor is implemented), there are already significant changes in 2030 generation-mix with respect to that of 2015. In Germany in 2030, fossil-based generation is 234 TWh in *REF* and below 150 TWh when there is a carbon price floor (*onlyDE*, *ClimaCoalition* and *allEUETS*). In all scenarios, the country becomes a net importer, despite the large growth of renewables (from 164 TWh in 2015 to at least 339 TWh in 2030). This trend continues in 2050, with renewables covering 86% of final demand. Still, in the absence of a carbon price floor, fossil-based generation in Germany remains above 100 TWh, which more than doubles that generation in *onlyDE*, *ClimaCoalition* and *allEUETS*. Hydrogen-based generation is only profitable when all the EU ETS members implement the carbon price floor, this technology generating 24 TWh in 2050 in *allEUETS*. Note that there is coal generation remaining even in *allEUETS* in 2050. This is consistent with Vögele et al. (2018), who, considering economic, political, technical elements, and social factors affecting the coal phase-out transition, conclude that the role of coal is limited to a "niche" in long-term, but could still be present in the generation-mix by providing backup to the market.

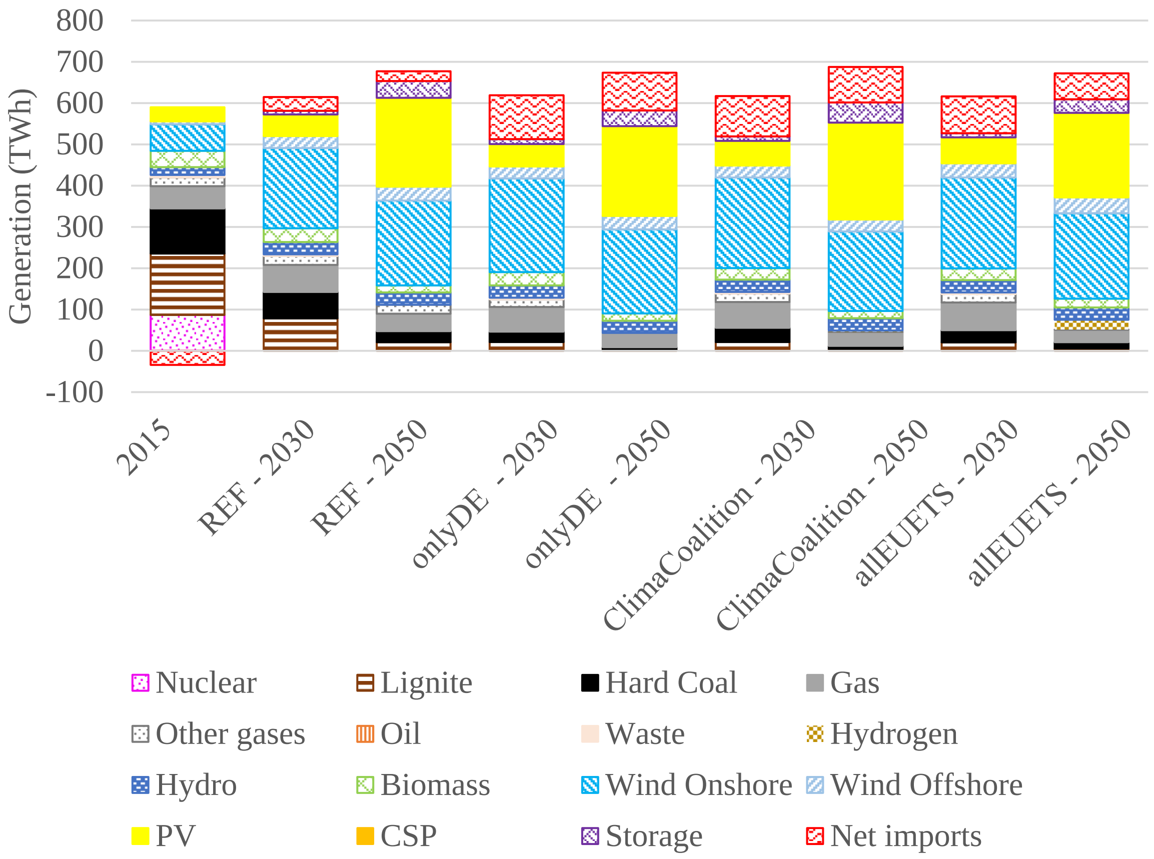



*Figure G1. Generation-mix in Germany in 2030 and 2050 for main scenarios evaluated. Values for 2015 are presented as a reference and are the same across all scenarios.*

At the EU ETS level, unlike at the German level, the generation-mix is very similar across scenarios *REF*, *onlyDE* and *ClimaCoalition*. In *allEUETS*, renewable generation is significantly larger in 2030 and 2050 than in the other scenarios. While countries implementing a carbon price floor invest largely in renewables, those just seeing the ETS price keep their fossil-based technologies longer. This ultimately explains the waterbed effect, which by 2050 is full. In *REF*, *onlyDE* and *ClimaCoalition*, the renewable share of final demand is up to 65% and 96% respectively in 2030 and 2050, while in *allEUETS*, this reaches respectively 72% and 103%. As a result, fossil-based generation in *allEUETS* is about a third of that in the other scenarios.

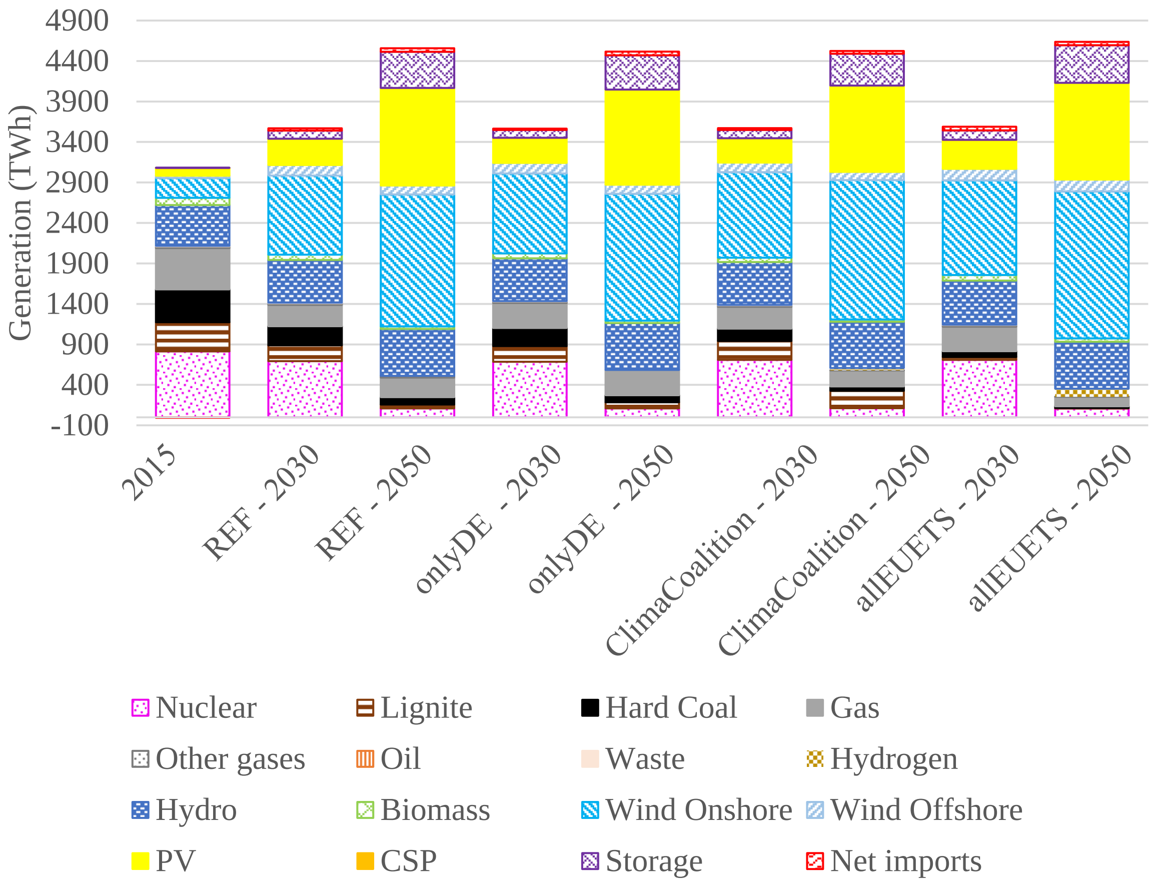



*Figure G2. Generation-mix in the EU ETS in 2030 and 2050 for main scenarios evaluated. Values for 2015 are presented as a reference and are the same across all scenarios.*

## H. The MSR

As explained in section 4.5, we use a simulation tool provided by Burtraw et al. (2018). Using the net change in electricity emissions when Germany or the coalition implement a carbon price floor, we calculate the resulting emission path. This path is used to estimate the bank and thus, simulate the MSR.

The MSR was created with an amendment of the Directive 2003/87/EC (European Commission, 2015a) and will start operating in 2019. The MSR has three main rules: (*a*) an amount $p\_intake$ is transferred to the MSR instead of being auctioned when the total number of allowances in circulation (TNAC) of the previous year is higher than 833 $MtCO_2$ ($upper\_threshold$), $p\_intake$ equalling 24% (until 2023 and 12% afterwards) of the TNAC size (Eq. (H.1)); ($b$) an amount $p\_outtake$ is transferred back from the MSR to the market when the TNAC of the previous year is lower than 400 $MtCO_2$ ($lower\_threshold$), $p\_outtake$ equalling 100 $MtCO_2$ (available through auctions) (Eq. (H.2)); and ($c$) when the size of the MSR stock is higher than the number of certificates to be auctioned in the previous year, the difference between both is cancelled from the MSR (Eq. (H.3)). With these parameters, we can simulate the MSR (Eq. (H.4)). Additionally, we consider an additional intake corresponding to the 900 million 'backloaded allowances' and the unallocated allowances during the rest of phase 3, which the European Commission (2015b) estimates between 550 and 700 $MtCO_2$. Following Burtraw *et al.* (2018), we assume these to be 250 $MtCO_2$ in 2019 and 1300 $MtCO_2$ in 2020 ($p\_extraintake_{t2}$) for a total of 1550 $MtCO_2$.

Initially, the certificates to be auctioned (planned auction, i.e., before subtracting/adding the certificates transferred to/from the MSR) equal 57% of the EU cap, $v\_planaucEUA_{t2}$ (Eq. (H.5)). The remaining certificates, $v\_freeEUA_{t2}$, are grandfathered (Eq. (H.6)). The realized auction depends thus on the intake to- and outtake from- the MSR (Eq. (H.7)). With these elements, we can simulate the TNAC (Eq. (H.8)).

$$\text{If } p\_TNAC_{t2-1} > upper\_threshold, \tag{H.1}$$

$$p\_intake_{t2} = min(p\_TNAC_{t2-1} \times rateintakeMSR_{t2}, v\_aucEUA_{t2}),$$

$$\text{in other case } p\_intake_{t2} = 0$$

$$\text{If } p\_TNAC_{t2-1} < lower\_threshold, \tag{H.2}$$

$$p\_outtake_{t2} = min(p\_MSR_{t2-1}, 100),$$

$$\text{in other case } p\_outtake_{t2} = 0$$

$$p\_cancellation_{t2} = 0 \quad \forall t2 \leq 2023 \tag{H.3}$$

$$p\_cancellation_{t2} = max(p\_MSR_{t2-1} - p\_aucEUA_{t2-1}, 0) \ \forall t2 > 2024$$

$$p\_MSR_{t2} = p\_MSR_{t2-1} + p\_extraintake_{t2} + p\_intake_{t2} - p\_outtake_{t2} - p\_cancellation_{t2} \tag{H.4}$$

$$v\_planaucEUA_{t2} = v\_cap_{t2} \times (1 - sharefreeEUA_{t2}) \tag{H.5}$$

$$v\_freeEUA_{t2} = v\_cap_{t2} \times sharefreeEUA_{t2} \tag{H.6}$$

$$p\_aucEUA_{t2} = v\_planaucEUA_{t2} - p\_intake_{t2} + p\_outtake_{t2} \tag{H.7}$$

$$p\_TNAC_{t2} = p\_TNAC_{t2-1} + p\_aucEUA_{t2} + v\_freeEUA_{t2} - v\_emi_{t2} \tag{H.8}$$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