Unilateral Action under an Emissions Cap

M. Pahle[a*], D. Burtraw[b], O. Tietjen[a], C. Flachsland[c,d] & O. Edenhofer[a,c,e]

December 26, 2018

Abstract

Cap-and-trade programs where multiple jurisdictions agree on a common cap such as the European Union's Emission Trading Scheme (EU ETS) face the challenge of how to accommodate different levels of ambition with respect to carbon mitigation, and respective preferences about technology pathways. Jurisdictions that value marginal benefits of mitigation above the average level have an incentive to take additional unilateral action, which has two important consequences: First, if the cap is binding, more mitigation in one jurisdiction would lead to less mitigation in other jurisdictions (waterbed effect). Second, unilateral action will reduce the price of allowances, leading to even higher motivation by environmental advocates for additional action, i.e. it creates a negative feedback on allowance prices. This could over time lead to a situation where "inactive" jurisdictions are more and more freed from their obligation to contribute to the public good provision. Both effects could endanger the integrity of cap and trade as a mechanism for cooperation, undermining stakeholder confidence and potentially putting its durability at stake. The EU ETS may be nearing such a state. In this paper, we investigate a price floor for allowances implemented as an minimum auction (reserve) price as a remedy to the waterbed effects. Using a numerical electricity market model (LIMES-EU) we investigate how such a price floor, implemented by a coalition or all EU-countries, compares to a reference case where the price is strictly determined by the demand for allowances and the emissions cap. We examine the impacts of a price floor on allowance prices, emission quantities, as well as auction revenues and consumer and producer surplus in each member state. We consider related distributional outcomes, such as potential gains for "inactive" member states that would potentially oppose a respective reform at the EU level. Findings show that a minimum price starting at 25 €/t in 2020 and rising at 5% per year would substantially alleviate the waterbed effect from the coal phase out policies envisioned in several EU member states, in particular in Germany. It implies withholding 3.9 Gt of allowances until 2050 in addition to the amount of allowances invalidated from the Market Stability Reserve (MSR) in 2023 as a result of the recent EU ETS reform. Implementing such a price floor creates both winners and losers, but overall effects are relatively small in magnitude and auction revenues increase for all member states. This indicates the availability of a number of options for creating a political coalition adopting such a scheme.

(*) Corresponding author: michael.pahle@pik-potsdam.de
(a) Potsdam Institute for Climate Impact Research, Telegraphenberg A 56, 14473 Potsdam, Germany.
(b) Resources for the Future, 1616 P St. NW, Suite 600, Washington, DC 20036, USA.
(c) Mercator Research Institute on Global Commons and Climate Change, Torgauer Str. 12-15, 10829 Berlin, Germany.
(d) Hertie School of Governance, Friedrichstraße 180, 10117 Berlin, Germany.
(e) Technische Universität Berlin, Straße des 17. Juni 145, 10623 Berlin, Germany.

1 Introduction

Achieving the goal of limiting global warming to below 2°C from pre-industrial levels envisaged by the Paris Agreement requires full decarbonization of the global economy by the end of this century (IPCC, 2014). Economists have pointed towards the importance of carbon pricing for minimizing the economic cost, which is essential to enable this transformation. This rationale is manifest in the European Union's Emissions Trading System (EU ETS), established in 2005, which remains the largest cap-and-trade system for greenhouse gases (GHG) in operation (World Bank 2017).

The EU ETS has developed an enduring market covering 31 countries with an annual asset value of 25 billion euros, enabled significant institutional learning (Convery, 2008), and provided a model that has propagated to carbon markets in North America and Asia (Bang et al., 2017). The market has strong compliance with meaningfully stringent emissions reduction goals; but only modest emissions reductions or innovation can be attributed to the market, in the face of other exogenous factors that have also driven down emissions (Martin et al., 2016; Calel and Dechezleprêtre, 2016). An important challenge has been a combination of low allowance prices that were a fraction of prices anticipated by modeling in the context of the European Commission's impact assessment of the 2020 climate and energy targets (Delbeke et al. 2009), and concurrently a large and growing bank of surplus allowances, equivalent to one year of emissions at the end of 2017.

In principle, low allowance prices should not be a problem in a cap-and-trade system because the cap determines the emissions outcome and low prices could be the result of innovation driven by carbon pricing. Similarly, a large bank is not a problem in principle. Depending on the time profile for the issuance of allowances and the opportunity cost of capital, a large bank might result from early over-compliance to enhance intertemporal cost-effectiveness, or might be acquired to smooth short-term shocks over time (Kling and Rubin 1997; Newell et al. 2005). In practice, however, persistent low prices and the large bank have posed a crisis of confidence in the program. They have raised concerns over the system's capability to incentivize cost-effective short-term abatement decisions such as fuel switching, or long-term abatement decisions including the low-carbon research and development and large-scale infrastructure investments required for full decarbonization. In general, the low prices and the large bank have raised doubts about the veracity of economic contributions to environmental policy (Edenhofer et al., 2017b).

We investigate these issues by developing a conceptual case for the introduction of a price floor and then employing a numerical simulation model to examine the market effects of various possible designs. We analyze the recently adopted quantity-based reform, the interaction of companion policies with the ETS, and various price floor scenarios, and we evaluate emissions outcomes, allowance price pathways and economic costs.

Multiple factors have contributed to both the low prices and large bank. The significant influx of cheap Clean Development Mechanism (CDM) credits from developing countries expanded supply, and the economic crisis reduced demand for allowances (Bel and Joseph, 2015). Companion (overlapping) policy instruments at the EU- and member state-level that incentivize deployment of renewable energy technology and energy efficiency also contribute to this outcome by reducing allowance demand like for example Germany's renewable energy policy (Weigt et al., 2013). The demand driven influence is called the "waterbed effect," as the total emissions volume is fixed by the allowance cap and companion policies simply shift emissions in time and space (FANKHAUSER et al., 2010).

The waterbed effect has objective and conceptual relevance for the EU. Rationales for companion policies include climate policy-related externalities such as learning-by-doing knowledge spillovers in renewable technologies (Jaffe et al., 2005), policy sequencing to build supportive constituencies for carbon pricing (Meckling et al., 2015), and heterogeneous preferences among jurisdictions regarding their level of climate policy ambition (Edenhofer et al. 2017, Chichilnisky and Heal (1994)). For example, ambitious countries may strive to exert international leadership by demonstrating aggressive greenhouse gas (GHG) mitigation to motivate others to do the same (Schwerhoff et al., 2018). They might also aim to achieve domestic co-benefits such as reduced local air pollution (Williams, 2012) or industrial policy goals in building a domestic low-carbon technology sector (Joas et al., 2016). Such considerations may explain the empirical prevalence of national and subnational level GHG reduction targets and companion policies even in the EU climate policy context. We refer to these companion policies and related policy goals as unilateral action underneath the umbrella of the EU ETS, and without comment here about the efficacy of these efforts, it is the view of many that the carbon market is not a sufficient instrument and companion policies are crucial to climate policy success in the EU. However, unilateral action under the umbrella of a cap-and-trade system always faces the challenge of the waterbed effect as the emissions cap not only specifies the maximum emissions but specifies actual emissions (Goulder and Stavins, 2011). Companion policies may bring no additional emissions reductions, at least in the short run, which undermines their legitimacy when they are implemented as climate policy.

Companion policies have been at least partly anticipated in the initial specification and subsequent reforms of the common EU ETS cap in the context of the 2020 climate and energy package (Capros et al., 2011). In practice, however, robust agreement on a common cap and the expected resulting price is difficult to achieve ex ante in the presence of uncertainty over multiple relevant factors including economic growth and technological and institutional change, and governments and climate policy preferences change over time. Ex post some member states have incentives to renege on the common policy design. Other member states, driven by constituencies with particularly intense preferences for emissions reductions, can be expected to implement additional unilateral policies intended to reduce emissions. The envisaged or de facto implemented coal exit policies in the UK, Germany, Austria and the Netherlands, support for renewable energy in several member states, carbon taxes in the UK and Sweden are cases in point. Without measures to account for the waterbed effect from these various sources, they will incur costs without affecting the emissions outcome; they will also drive down prices and increase the bank, and undermine the use of prices to coordinate cost-effective mitigation. Consequently, advocates favoring these companion policies have expressed sharp criticism of the carbon market, reviving the ethical debate about carbon pricing , and posing a threat to the market's political sustainability.

Largely as a response to these challenges and following earlier reform efforts, in 2015 the EU initiated a mechanism called Market Stability Reserve (MSR) that withholds allowances from the market based on the number of allowances in circulation, and in 2018 took the further step of cancelling some of those withheld allowances beginning in 2023 (EC, 2015, 2018). Anticipated implementation of this quantity-based approach has already influenced prices and is expected to reduce the allowance surplus, although it is not expected to fully ameliorate the waterbed effect (Perino, 2018). However, its operation is opaque and its effects are not easy to predict. Some argue that the introduction of price-based mechanisms, e.g. a minimum market price even when exogenous factors reduce allowance demand, is required to remedy the system's fundamental problems (Edenhofer et al., 2017a).

This paper contributes an assessment of the recent quantity-based reform and suggests a novel rationale for introducing a floor price, even with this reform in place. Our argument draws on two well-established lines of analysis. We combine literature analyzing the waterbed effect with the challenge of establishing credibility in climate policy, hypothesizing a negative feedback loop between the two. Our argument is that persistently low prices and a large bank can be the result of a lack of policy confidence, as well as a source of uncertainty about the stringency and persistence of the system.

We conjecture that implementing a carbon price floor, or more generally making the allowance supply function in emissions markets more price-responsive, can interrupt this dynamic. A price floor may instead create a virtuous cycle in which low-carbon investment decisions can be made based on a more predictable carbon price (Burtraw et al., 2010; Wood and Jotzo, 2011). Companion policies might not threaten to undermine this lower-bound price signal while achieving other goals, and both dynamics might combine to restore and strengthen market confidence and policy effectiveness in a positive feedback loop.

A price-based mechanism reduces the waterbed effect through automatic withdrawal (and presumably cancellation) of allowances from the market when allowance prices fall to a threshold level. Efforts to enforce a minimum price is a familiar in many commodity markets (Salant, 1983). Emissions markets under the Regional Greenhouse Gas Initiative (RGGI) involving nine eastern U.S. states, and under the Western Climate Initiative involving California, Ontario and Quebec, both coexist with prominent companion policies implemented by the participating jurisdictions (CARB, 2011). In these programs, minimum prices are implemented as an auction reserve price. If the auction price falls to the reserve price, some allowances do not enter the market, constraining supply and supporting the price. The auction reserve price has been triggered in both North American programs, providing buoyancy to the programs during periods of low demand and subsequently in both programs the auction price has risen above the floor. This has preserved the market institution and implicitly the value of investments when otherwise, at least in RGGI, over-allocation would likely have led to a zero price and cessation of the market. The RGGI program has also recently introduced an additional price step to incrementally constrict supply at a price above its price floor, resulting in a price-responsive allowance supply schedule.

Heterogeneous willingness to pay to mitigate emissions among nations and the incentive to free ride has sparked the suggestion for a climate policy club, which might ultimately impose penalties on bad actors and nonparticipants Nordhaus (2015). The EU represents such a club, but even within the EU as in other linked trading programs, participating jurisdictions exhibit varying levels of ambition. Methods to achieve cooperation within the club is essential. One might argue that an effective way to express heterogeneous climate policy preferences within a multilateral cap-and-trade system would be through targeted compensation as part of bargaining over the common level of ambition (i.e., the cap). Not surprisingly, such bargaining has been observed in past EU ETS reform processes (Dorsch et al., 2018), but the political scope for international compensatory transfers is limited. Hence, we draw attention to the possibility for a price floor to initiate implicit transfers through the change in auction revenues among member states. We observe also that state-specific price floors are envisaged by France and Netherlands and discussed by others. We investigate if a price floor implemented by a coalition subset of EU member states would enable those states to more directly contribute to system-wide emissions outcomes, and achieve implicit transfers to other states with less intense preferences for climate policy by increasing those states' auction revenues.

Using a numerical simulation model under a range of assumptions, we find the MSR as we are able to represent it has a positive but modest effect on the allowance price path. A minimum price of 15 € per ton or 25€ per ton, rising at 5 percent per year, has a significantly greater effect and that effect remains even if the minimum price is applied on top of the MSR. We also explore distributional effects across and within EU member states, finding that Germany and Poland both lose economic surplus under the minimum price, while some nations such as France gain surplus. The effects on the emissions are the same if the minimum price is implemented across the EU or only by a subset coalition of member states, but the differences between the winners and losers is magnified if the minimum price is enforced by only a coalition of countries. Section 2 provides further institutional background for the EU ETS, and describes how the price floor fits into the literature on economic approaches to environmental policy and. Section 3 offers a conceptual model to analyze distributional effects in an intertemporal ETS. Section 4 presents results from the intertemporal optimization model LIMES-EU. Section 5 presents our results and Section 6 concludes.

2 Background

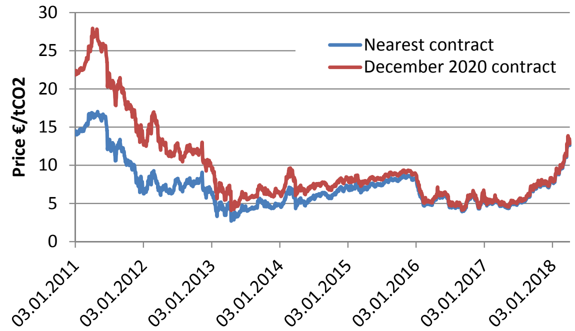
The EU ETS has evolved substantially from its inception in 2005, when virtually all allowances were distributed for free based primarily on historic activity, to a system today when all the allowances distributed to the electricity sector are auctioned, with some special exceptions, and soon most of allowances in the EU will be distributed by auction (Ellerman et al., 2016). Auctions involving various of the member states happen almost daily. It is seldom mentioned, but in fact these auctions have a price floor to guard against collusion and possible unintended sale at a very low price if bidding fails to materialize. However, the price floor is not announced in advance and is kept secret, out of concern that its price level might affect bidding behavior. If bids were insufficient to match supply at this price, the auction would be cancelled and allowances would be distributed through a subsequent auction.

Various reforms have managed to boost the allowance price on a short-term basis, but until recently the long-run trend has been for prices to settle below 10€/tCO2. In 2015, the EU ETS adopted a quantity-based approach to address the dual challenges of a low allowance price accompanied by a large emissions bank. The EU delayed ("backloaded") the issuance of a large volume of allowances and introduced the Market Stability Reserve (MSR), which would automatically restrict the quantity of allowances to be sold in the auction and direct the unsold allowance into the MSR when the quantity of allowances in circulation exceeds a threshold value. Allowances held in the MSR could be returned to circulation if the number of allowances falls below a low threshold value. Analysts were generally skeptical of the effectiveness in delaying the sale of allowances, however, because with banking, the allowance price in the present should anticipate the expanded supply that would ultimately occur (Hepburn et al., 2016; Fuss et al., 2018).

In February 2018 the EU finalized additional important reforms. In Phase 4, beginning in 2021, the total amount of allowances issued will be reduced at 2.2 percent per year instead the previous rate of 1.74 percent. Secondly, starting in 2019, a part (initially 24 percent, then 12 percent from 2024) of the allowance surplus (number of allowances in circulation) will be withheld from the next year's auction and moved to the MSR. Third, the volume of allowances that can be held in the MSR will be limited to the previous year's volume of auctioned allowances and the difference will be eligible for cancellation, permanently affecting the long-run supply. Estimates indicate this provision may result in the retirement of over 2 billion allowances in 2023, in comparison to a current annual cap of about 1.6 billion, which continues to decline. These reforms appear to have already had a short-run effect allowance prices (see figure 2.1), leading to anticipation of a positive long-term impact in supporting prices and providing a partial remedy to the waterbed effect.

The MSR (with the cancellation provision included) adjusts the number of allowances in circulation with a lag that can take several years to implement. Several authors express concern that this mechanism lacks transparency and has unhelpful complexity, and will remedy the waterbed effect

Figure 2.1: Historic EU ETS allowances prices



only partially and for a limited period (Perino, 2018). It is worth noting that while the rule-based quantity intervention via the MSR is expected to and is already affecting allowance prices, a price-based approach to managing allowance supply is dual to the quantity-based approach. However, the administration of a price-based approach is certainly more transparent and easier to grasp.

The price-based approach to constraining market outcomes is implemented through a reserve price in the allowance auction. This approach is a modification of an inelastic supply schedule, and offers a hybrid of quantity- and price-based mechanisms, as first discussed by Roberts and Spence (1976). Pizer (2002) shows in the presence of uncertainty that combining a price and quantity is more efficient than either mechanism alone, but up to that time the introduction of a price floor was viewed as impractical because authors imagined it would have required the government to buy back emissions allowances that presumably had been distributed for free (Baumol and Oates, 1988). However, revenue raising auctions are now a prominent feature of allowance trading systems and the minimum price can be enforced with a reserve price. The reserve price can also be implemented with free allocation using a consignment auction (Burtraw and McCormack, 2017), which is used in California and is proposed in the state of Virginia as it seeks to link with RGGI. A price-responsive supply could include multiple price steps or a continuous schedule of allowance supply that are available at an increasing schedule of allowance prices (Burtraw et al., 2018).

In contrast with the MSR, ease of administration may be an advantage of a price responsive allowance supply. As we discuss below, the identification of a minimum price that would achieve the same result as the MSR is difficult. The mapping of the effects of the MSR onto expected prices is also difficult, but that is ultimately necessary for firm investment decisions. The simplicity of a minimum price may be valuable to the evolution of stakeholder perceptions for the durability of the market and the performance and reform of policy mixes over time (Pahle et al., 2017). But crucial to the effectiveness of the price floor is likely to be what becomes of the allowances that do not sell in the auction. If the allowances roll over to the next auction, then cumulative supply is unaffected and short-run mitigation, marginal costs and prices may not be affected either. In RGGI, the first jurisdiction to implement a price floor, the allowances that do not sell are held in a holding account until a regularly scheduled program review can determine their fate. Precedent is that all the unsold allowances have subsequently been canceled, and this is the expectation going forward. Surprisingly, though, allowances that do not sell under the emissions containment reserve (the price step above the price floor) are automatically canceled. In California, unsold allowances are held out of the market until all the allowances intended for sale are sold in two consecutive auctions; thereafter the withheld allowances slowly reenter the market through subsequent auctions. However, legislation authorizing the extension of the state's cap and trade program through 2030 explicitly directed that the unsold allowances be removed from the auction and placed in a reserve that would enter only at high prices.

A major argument against introducing a price floor in the EU ETS has been concern over the legal viability of any provision with price-based targets, as taxes require unanimity decision-making under the constitution of the European Union. In fact, the EU ETS has only been introduced after many years of unsuccessfully attempting to introduce a EU carbon tax because it was possible to apply majority voting rules. In a recent analysis, however, legal experts argue that an auction price floor is legally different from a tax and would thus be exempt from related EU decision-making procedures (Fischer, 2018). A similar legal test in California validated its carbon market program and affirmed in 2017 that its auction with a price floor do not equate to a tax.

3 The model

3.1 General setup

While the EU ETS regulates emissions in both energy production and energy-intensive industry sectors, we only consider the power sector here. Let the different countries (EU member states) be indexed by s and have different price-inelastic electricity demand d_{st} that varies between years t. The markets of individual states are linked, but transmission capacity between two states $\bar{l}_{s,s'}$ may be limited. Accordingly, wholesale electricity prices w_{st} may differ between states. Let each state have a representative electricity supplier that uses different technologies i to generate electricity q_{sit}. Marginal generation cost c_{it} is constant in production but may vary over years, and emission intensity is β_i. In-state supply from all technologies, which must not exceed installed capacity $\bar{q}_{sit}$ in any year, plus net imports ($l_{s,s't}$) from all linked markets matches demand in equilibrium:

$$d_{st} = \sum_i q_{sit} + \sum_{s'} l_{s,s't} \tag{3.1}$$

$$\bar{q}_{sit} \geq \widetilde{q}_{sit}; \bar{l}_{s,s'} \geq \widetilde{l}_{s,s't} \tag{3.2}$$

Existing generation capacity depreciates at rate γ between years, and investments in new capacity is given by $k_{sit} \geq 0$ incurring per unit investment costs fc_{it}. The state equation for capacity is thus:

$$\bar{q}_{sit+1} = (1-\gamma)\,\bar{q}_{sit} + k_{sit} \tag{3.3}$$

Electricity markets in all states are regulated under a common emission trading system (ETS). Compliance requires that electricity suppliers must submit allowances equal to their total emissions by the end of a year. Excess allowances may be banked for future compliance. The number of banked allowances by the representative firm is given by b_{st}. Annual emissions of the firm in state s are $e_{st} = \sum_i \beta_i q_{it}$ and its annual purchase of allowances is y_{st}. The dynamic banking condition and the non-negativity constraint for the bank (no borrowing) therefore are

$$b_{st+1} = b_{st} - e_{st} + y_{st} \tag{3.4}$$

Table 1: Model variables and parameters

Variable	Description	Unit
d_{st}	electricity demand in state s and year t	MWh
w_{st}	wholesale electricity price in state s and year t	EUR/MWh
q_{sit}	electricity production by technology i in state s and year t	MWh
c_{it}	marginal cost of generation of technology i in year t	EUR/MWh
β_i	emission intensity of technology i	tCO2/MWh
$\bar{q}_{sit}$	installed generation capacity of technology i in state s and year t	MW
$\widetilde{q}_{sit}$	maximum electricity production by technology i in state s and year t	MW
k_{sit}	investments in new generation capacity of technology i in state s and year t	MW
fc_{it}	specific investment costs for new generation capacity of technology i in year t	EUR/MW
γ	annual capital depreciation rate	
r	discount rate	
$\bar{l}_{s,s'}$	(net) transfer capacity between state s and s'	MW
$l_{s,s't}$	total flow of electricity between state s and s' in year t	MWh
$\widetilde{l}_{s,s't}$	maximum flow of electricity between state s and s' in year t	MW
...		
e_{st}	total annual emissions in state s	tCO2
y_{st}	total annual purchase of allowances in state s	tCO2
b_{st}	number of allowances banked by firms in state s and year t	tCO2
p_t	price of allowances in year t	EUR/tCO2
$\bar{x}_{st}$	allocation of allowances to state s in year t	tCO2
x_{st}	allowance sold by state s in year t	tCO2
$\bar{X}$	total number of allowances in compliance period (cap)	tCO2
$\underline{p}_{st}$	auction reserve price set by state s in year t	EUR/tCO2

$$b_{st} \geq 0 \tag{3.5}$$

Let p_t be the allowance price which is the same in all states because allowances are tradable among them without restrictions. Using discount factor r, the profits of the representative firms are given by:

$$\pi_s = \sum_{t=0}^{T} \sum_{i=0}^{I} r^t \left(\left(w_{st} - c_{it} \right) q_{sit} - y_{st} p_t - f c_{it} k_{sit} \right) \tag{3.6}$$

The decision problem of the representative firm is thus to maximize (3.6) by deciding on production q_{sit}, investments k_{sit} and allowance purchases y_{st} subject to (3.2) - (3.5).

The price of allowances is determined by overall demand (as describe above) and supply. Regarding the latter, a certain number of allowances per year denoted $\bar{x}_{st}$ is apportioned to each state for auctioning so that the sale of allowances in a compliance period sums up to the aggregate and cumulative cap given by $\bar{X} = \sum_{s,t} \bar{x}_{st}$. State regulators are free to set an auction reserve price $\underline{p}_{st}$, implying that they may not sell all their allowances if the price of allowances is at that price ($p_t = \underline{p}_{st}$), and would not sell any allowances if the allowance price is below their reserve price ($p_t < \underline{p}_{st}$). Importantly, not selling allowances in the auction decreases allowance supply and thereby increases the overall price of allowances as captured in the following equilibrium condition:

$$p_t - \underline{p}_{st} \geq 0 \quad \perp \quad 0 \leq \bar{x}_{st} - x_{st} \quad \forall s, t \tag{3.7}$$

In addition, total sales must not exceed apportioned quantity

$$0 < x_{st} < \overline{x}_{st} \tag{3.8}$$

and equilibrium in the annual allowance market requires that aggregate supply in a year ($X_t = \sum_s x_{st}$) equals allowance purchases

$$X_t = \sum_s y_{st} \tag{3.9}$$

which is satisfied by the allowance price p_t.

When one or more states implement reserve prices, this corresponds to a step-wise linear supply function for allowances as in RGGI's emission containment reserve (ECR) model (Burtraw et al. 2017). One special case of such a function is when a "coalition" of states agrees on common reserve price, and all other states auction allowances without restriction.

To determine the welfare effects of implementing auction reserve prices on individual or all states, we decompose state welfare as follows:

$$W_s = CS_s + PS_s + R_s \tag{3.10}$$

The first component CS_s is consumer surplus. Since demand is fixed, consumers have an infinite high value for electricity. Assuming that the value is capped at some point and ignoring the benefits (which are fixed and thus always the same), the consumer surplus can be measured by the (negative) costs of electricity, $CS_s = -\sum_t r^t d_{st} w_{st}$. Correspondingly, the change in consumer surplus depends on the change of electricity prices and is given by$\triangle CS_s = -\sum_t r^t d_{st} \triangle w_{st}$.

Producer surplus is equal to the profits of the representative firm as given by 3.6. While for new investments profits are always zero in the long-run equilibrium, this is not the case for existing capacities when policy changes unexpectedly as analyzed here.

The last welfare component is revenues from auctioning, which are given by $R_s = \sum_t r^t p_t x_{st}$. The change in this component also needs to consider forgone revenues, and is thus given by

$$\triangle R_s = \sum_t r^t \{\triangle p_t x_{st} - p'_t(\overline{x}_{st} - x_{st})\} \tag{3.11}$$

where p'_t is the (higher) allowance price in the case where an auction reserve price is implementedt. The first term is positive and captures additional revenues due to the higher allowance price for the share of allowances that is sold in the auction. The second term is negative and captures forgone revenues from the unsold share of allowances due to the implemented reserve price. That is, states that implement a reserve price realize an increase in revenue if the first term is larger than the second one and vice versa.

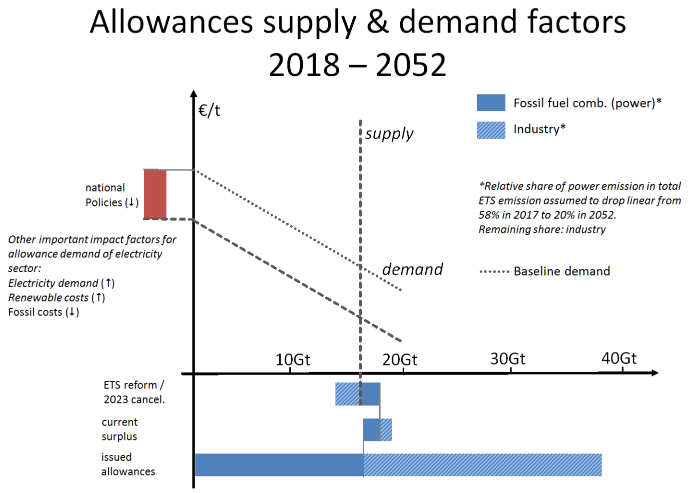
3.2 Assumptions & Scenarios

3.2.1 Assumptions

As outlined above, allowance price formation and the effects of auction reserve prices depend on various factors and related assumptions. One key factor is the intertemporal supply of allowances, which we consider in the period 2018-2052 corresponding to the model years 2020-2050. It has three main components that are decomposed in the horizontal bars in figure X: (a) annually issued allowances as determined by the linear reduction factor (LRF), (b) the current market surplus (bank), and (c) the cancellation of allowances in 2023 in the MSR as decided in the recent ETS reform. Regarding (a) and considering the increase of the LRF to 2.2% as decided in the recent ETS reform, the total number of allowances to be issued between 2018 and 2052 amounts to around 38.1 Gt . Regarding (b), the total surplus at the end of 2016 amounted to around 1.7 Gt of allowances, and additional 0.9 Gt of allowances were back-loaded (EEA 2017). We assume that the surplus by the end of 2017 is still 1.7. Since we do not model the MSR explicitly, we add the back-loaded allowances to the surplus and thus have in total an initial bank of 2.6 Gt in 2018. Regarding (c), we abstract from the details of the cancellation rule and assume that 2 Gt will be canceled in 2023 (REFS: Perino, ICAP). Under all these assumptions, the cumulative overall supply of allowances in the period 2018-2052 is thus 38.7 Gt.

As we only consider the power sector, assumptions over the share of allowances used for compliance in the other sectors are crucial. According to the EU reference scenario (EC 2016), the share of power sector emissions in total EU ETS emission declines from 58% in 2015 to 41% in 2050. That is, there is more abatement in the power sector due to lower abatement costs compared to the other ETS sectors. The EU reference scenario, however, does not take the latest ETS reform into account. The higher LRF of 2.2% from 2020 onwards and the expected cancellation of allowances due to MSR in the early 2020s is not considered. Therefore, the overall allowances issued between 2018 and 2052 would have been 46.1 Gt and thus about 7.4 Gt higher compared to the updated data (see above). In line with the typical finding that abatement costs in the power sector are less expensive relative to other sectors (REF) we assume that a larger part of the additional abatement is achieved in the electricity sector as follows: the share of power sector emissions declines linearly from 58% in 2015 to 20% (instead of 41% as in the Reference Scenario) in 2050 and correspondingly also the share of allowances with it. Likewise, we assume that 58% of the recent allowance surplus

Figure 3.1: Waterfall diagram indicating cumulative EU ETS allowance supply 2017-2052



of 2.6 Gt (see above) will be used in the power sector. Hence in sum about 16 Gt of allowances are available in the power sector between 2018 and 2052. For the MSR cancellation this implies that 1.03 Gt CO2 are deleted in 2023 (2 Gt * 51.5% electricity sector share in 2023 = 1.03 Gt). An overview of of the overall calculation of supply and demand is shown in figure 3.1.

Of importance for analyzing the effects of a minimum price is the share and distribution of auctioned allowances, because it constraints how many allowances can be withheld in each year and by whom. In 2015 41% of all allowances (624.8 Mt out of 1519 Mt) were auctioned (EEA 2017, Table 1.3). However, we assume that all allowances we ascribe to the power sector are auctioned and apportioned to EU member states based on the historic emissions between 2005 and 2007 as shown in Table (2).

An important additional factor determining allowance price formation and effects from auction reserve prices is the discount rate. Given that there is substantial uncertainty about how the ETS will evolve in the future - and particularly in the years after 2030, for which no climate and energy targets have yet been formulated. In face of that we assume a risk-adjusted discount rate of 10%, resembling required rate of returns, approximating observations in the electricity markets.

3.2.2 Baseline scenario

We consider two different baseline scenarios. B1 is a hypothetical baseline scenario primarily used for diagnostic purposes, in which the EU ETS is the only mitigation policy implemented. In B2, our central case baseline for this investigation,some states have additional national policies in place, which overlap with the EU ETS and thus imply a waterbed effect. The B2 baseline scenario explicitly accounts for anticipated member state actions to promote renewables and phase out coal.

Typically renewable energy policies have been named in that context in the past, but recent developments in the EU suggest that this might not be the case in the future. In many EU member states renewable policies had been implemented in the past primarily to comply with the

Table 2: Apportioned share in overall auctioned allowances

Austria	1.50%
Belgium	2.78%
Bulgaria	1.63%
Croatia	0.54%
Czech Republic	3.68%
Denmark	1.25%
Estonia	0.57%
Finland	1.77%
France	6.44%
Germany	21.88%
Greece	3.08%
Hungary	1.23%
Ireland	0.95%
Italy	10.33%
Latvia	0.12%
Lithuania	0.48%
Luxembourg	0.12%
Netherlands	3.82%
Norway	1.12%
Poland	9.42%
Portugal	1.60%
Romania	3.10%
Slovakia	1.21%
Slovenia	0.37%
Spain	8.36%
Sweden	0.98%
United Kingdom	11.66%

Table 3: Renewable energy targets on the member state level

Country	Share of renewable energies [%] (2016)	Targets
Germany	30	2025: 40-45% 2030: 65% 2050: 80%

EU-wide target of 20% in gross final energy consumption by 2020, which was broken into legally binding targets for each state. Recently this target has been extended to 27% by 2030, but without formulating legally binding targets for each member state any more. In face of this the prospects of renewable support post 2020 are relatively uncertain, and some member states have already announced their intent to drop respective targets. Notably Poland, the second largest emitter in the power sector after Germany, is bound to fall short of its 2020 target.[1] Against this background, we only consider renewable energy policies if they are an integral part of the national climate and energy strategy, for which we consider enactment in national law and underpinning by a long-term target as an appropriate indicator. To the best of our knowledge, this is only the case for Germany, where legally binding targets until 2050 exist since 2011. Recently, the new governing coalition has announced its intention to scale up the 2030 target to 65%.

Probably more relevant for the coming decade are plans to phase out coal. Several EU member states (see table 4) have joined the Powering Past Coal Alliance (PPCA) in 2016 and thus pledged to "*phasing out existing traditional coal power in their jurisdictions, and to a moratorium on any new traditional coal power stations without operational carbon capture and storage within their jurisdictions*". So far relatively little action has been taken except for the UK, which in early 2018 [2] confirmed its plans to phase out (unabated) coal by 2025. To achieve that goal, the UK relies on (a) a top-up carbon price (climate change levy), (b) the effects of European regulation (Large Plant Combustion Directive), and (c) and a planned emission intensity standard (450gCO2/kWh) to be implemented in the future. However, there seems to be increasing momentum for a coal phase out; for example Austria and the Netherlands have announced measures that would effectively end the use of coal. Moreover, the new German government will set up a commission to develop measures and propose a final date for phasing out coal. For the baseline scenario we assume that Germany will eventually decide to phase out coal by 2035. This assumption is of some importance as Germany has by far the highest emissions from coal among all the EU member states planning to phase out coal. Table 4 gives an overview about the targets of the PPCA states. In addition it includes Germany, for which we assume a coal phase-out in 2035.

3.2.3 Policy scenarios

In the policy scenarios, one or more member states set a reserve price in the allowance auctions. We define these scenarios by distinguishing the states that set a reserve price and the level of the reserve price. We distinguish between a scenario in which all EU ETS states (S1) and one in which a coalition sets a reserve price (S2). The coalition consists of the PPCA signatories and Germany (cp. previous section). The level of the reserve in 2020 is either 15€, or 25€ per ton and grows at the social discount rate of 5% each year. Table 5 gives an overview of the scenarios we consider.

[1] TU Wien & Ecofys, 2017: 2020 Renewable Energy Target Realisation Forecast for Poland Final Report. Link

[2] UK Government, 2018: IMPLEMENTING THE END OF UNABATED COAL BY 2025. Government response to unabated coal closure consultation. Link

Table 4: Emission from coal power plants and assumed coal phase out date

Country	Emissions form coal power plants [Mt] (2016)	Phase out completed by...
Austria	2	2025
Belgium	-	-
Denmark	8	2030
Finland	7	2030
France	8	2020
Germany	255	2035
Ireland	4	2025
Italy	33	2025
Latvia	-	-
Lithuania	-	-
Luxembourg	-	-
Netherlands	30	2030
Portugal	11	2030
Sweden	1	2020
United Kingdom	28	2025

Note: Germany is the only country that has not signed the Powering Past Coal Alliance (Source: www.beyond-coal.eu/data).

Table 5: Scenario matrix

	baseline scenarios	policy scenarios	
Reserve Price	None	All (S1)	Coalition (S2)
EU ETS	B1	B1_S1	B1_S2
EU ETS + national policies	B2	B2_S1	B2_S2

Note: we write B1_S1_15 for a reserve price of 15€ and B1_S1_25 for a reserve price of 25€ in 2020. Reserve prices always grow with the social discount rate of 5%.

3.3 Numerical implementation

We implement the approach of the previous section in the linear cost minimization model LIMES-EU[3]. That is, instead of having representative firms that maximize profits and states that decide about the amount of allowances they sell, we have only one objective function which becomes:

$$\min_{q_{sit},k_{sit},y^f_{kst}} \sum_{t=0}^{T}\sum_{s=0}^{S}\beta^t\left(\sum_{i=0}^{I}(c_{it}q_{sit}+fc_{it}k_{sit})-\sum_{k}^{K}p^f_{kst}y^f_{kst}\right)$$

The problem is constrained by (in)equalities (3.1) to (3.3) and (3.8). Instead of dynamic banking conditions for representative firms as in (3.4) and (3.5), there are only aggregate banking conditions:

$$B_{t+1} = B_t - E_t + \bar{X}_t - \sum_s\sum_k p^f_{kst}y^f_{kst} \tag{3.12}$$

$$0 < B_t \tag{3.13}$$

where the upper case letters indicate the sums over the states. An initial surplus of certificates is reflected by $B_0 > 0$ and the non-negative constraint for B_t is again due the borrowing constraint (which is not allowed as in current EU ETS legislation). The implementation of the reserve price is in line with the approach described by Fell et al. (2012).

It can be easily shown that this cost minimization problem leads to the same results as the decentralized problem of the previous section. Finally, note that there are more parameters and constraints in the LIMES-EU model not shown here (e.g. transmission investments and constraints, ramping constraints for plants) to keep the model description simple.

4 Results

4.1 Baseline scenarios and the waterbed effects

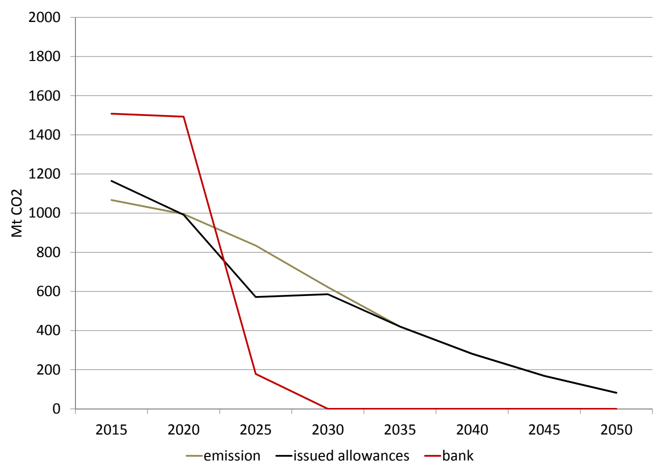
Figure (4.1) shows how emissions, issued allowances and the bank evolve over time. What stands out in both cases is the kink in issued allowances between 2020 and 2030, which reflects the 2023 cancellation of allowances through the MSR as explained in section (3.2). While the actual number of canceled allowances will depend on a complex rule featuring a number of parameters, we assume it to be constant. We consider alternative MSR cancellation quantities in section (4.3).

In addition to the temporal dynamics, the waterbed effect also has a spatial component. Additional national policies lead to lower prices, and in turn member states without national policies emit more compared to scenario B1. Figure (4.2) shows that the allowance price is below 20 €/t in 2030 in scenario B2, while it exceeds 40 €/t in scenario B1. Note that the ETS price rises at the discount rate if the borrowing constraint is not binding, i.e. as long as there is a positive bank. In case the borrowing constraint binds, the ETS prices rises at a lower rate. This explains the price drop in scenario B1 and the very low growth rate in scenario B2 between 2045 and 2050.

[3] https://www.pik-potsdam.de/research/sustainable-solutions/models/limes

Figure 4.1: Emissions in baseline scenarios

(a) baseline without national policies (B1)



(b) baseline with national policies (B2)

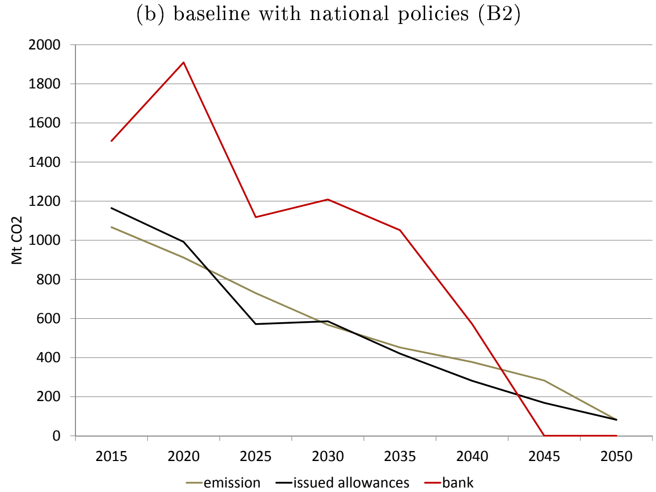
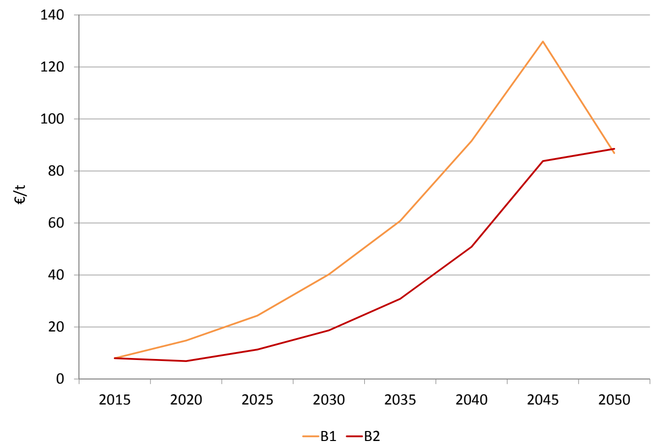


Figure 4.2: ETS prices in baseline scenarios



4.2 Policy scenarios: Impact of minimum prices

In this section, we analyze the effect of price floors set at 15 or 25 €/t in 2020 and rising at 5% each year. We assume that price floors are implemented as auction reserve price by those member states that also have implemented additional national policies (policy scenarios S2). We consider alternative assumptions in section (4.4).

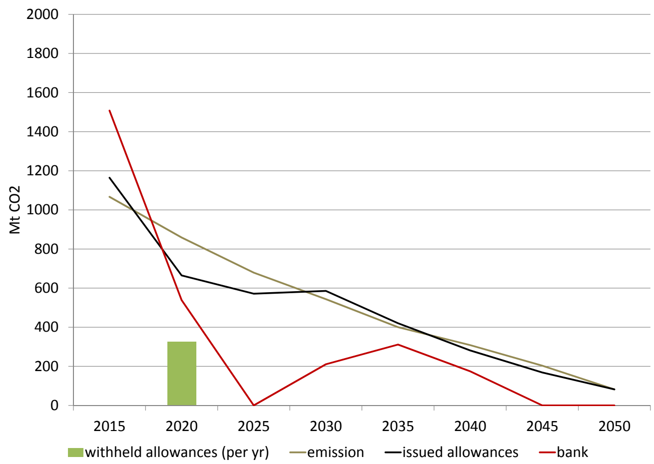
4.2.1 Emission and CO2 prices

In order to reach the minimum price of 15 €/t, 327 Mt allowances are withheld per year on average in the 2020 five-year-period, equaling 1,635 Mt allowances in total. This leads to the bank being drawn down to zero in 2025, in contrast to hitting zero only in 2045 in case of no minimum price (cp. scenario B2 in figure (4.1)). Notably, no allowances are withheld after 2025 because allowance scarcity drives prices up at least as high as the minimum price as can be seen in figure (4.4). In order to reach a minimum price 25 €/t in the 2020 period, 2,720 Mt allowances are withheld in this time step. The relatively high minimum price also requires allowances to be withheld in 2030, 2035 and 2050. Consequently, total withheld allowances are 3,943 Mt and thus around 2.4 times higher than in the 15 €/t case. Further note that the effect of the MSR cancellation of 1,030 Mt allowances has a significantly smaller effect on the aggregate allowance supply than either of the price floors.

Figure (4.4) also implies that the coalition of countries implementing the reserve price can withhold sufficient allowances to actually reach the targeted price floor. More allowances are withheld in early years because firms have a higher discount rate (10%) than the rate of increase of the price floor (5%). Therefore, the market allowance price rises at a higher rate compared to the minimum price as long as the borrowing constraint is not binding. Put differently, the high discount rate of the firms leads to a higher allowance price in later years, rendering the price floor less relevant over time.

Figure 4.3: Emissions in policy scenarios

(a) reserve price: 15€ (B2_S2_15)



(b) reserve price: 25€ (B2_S2_25)

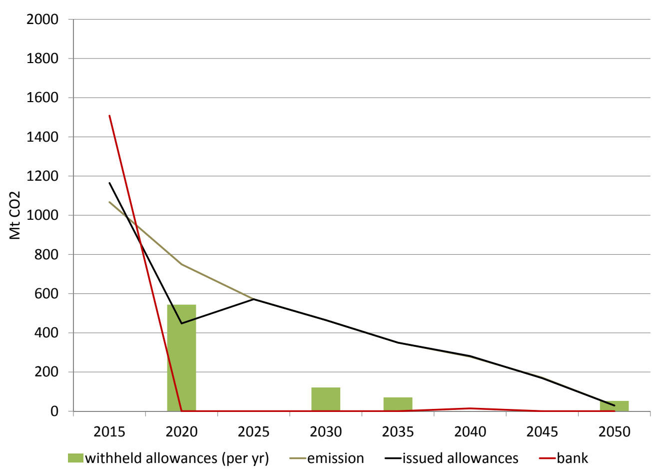
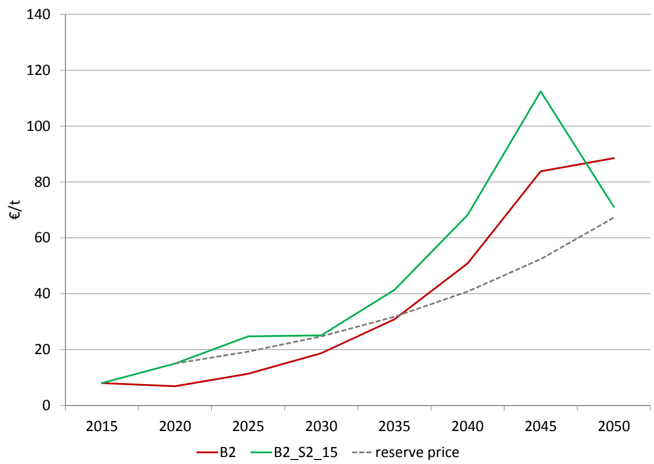
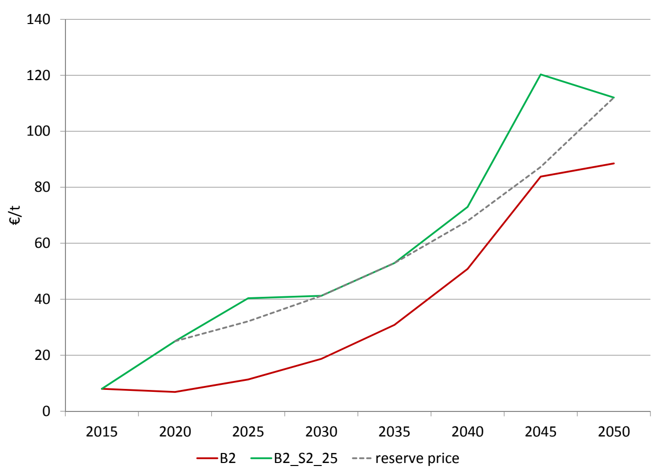


Figure 4.4: CO2 prices in policy scenarios

(a) reserve price: 15€ (B2_S2_15)



(b) reserve price: 25€ (B2_S2_25)



4.2.2 Wealth effects

In this section, we consider the wealth effects of minimum prices. Specifically, we analyze the wealth effects for different member states triggered by price floors in the policy scenarios compared to baseline scenario B2. We decompose wealth effects into changes in auction revenues and producer and consumer surplus.

Figure (4.5) reveals that Germany, Italy and Poland bear the largest net total costs of implementing a reserve price. Cumulated welfare losses are -8.1, -3.6 and -3.1 billion € respectively in the case of a minimum price of 15 €/t. On the other hand, countries like Norway, Sweden and especially France benefit with 0.7, 0.8 and 2.2 billion €. A minimum price of 25 €/t preserves the set of losers and winners, but not surprisingly effects are stronger.

The most important factor determining whether a country is a net loser or winner is the change in producer surplus. German and Polish producers lose because of their currently large shares of coal in power generation. By contrast, French and Austrian producers feature very high shares of clean nuclear and hydro generation respectively which benefit from rents incurred by a minimum price. Spain and Italy are intermediate cases, having both significant coal capacity as well as clean capacity (especially wind and solar PV). Moreover, given the relatively old age structure of their fossil-fuel fleets, a minimum price leads to an accelerated capacity turnover adding clean capacity. Therefore, on aggregate producers in these two countries benefit despite the relative high share of coal. However, consumers lose in all countries because the higher CO2 prices leads to higher electricity prices. This obviously holds for relatively high emitting power systems like Germany and Poland, but also for the intermediate case of Spain, as well as France featuring hardly any fossil generation capacities. The reason is that in these countries, electricity prices are often determined by relative high emitting plants at the margin and thus are significantly affected by a higher CO2 price. Finally, all countries incur higher auction revenues due to a price floor. That is, even countries that implement a reserve price like Germany benefit fiscally because the inframarginal price effect dominates the quantity effect of a lower number of auctioned allowances (3)).

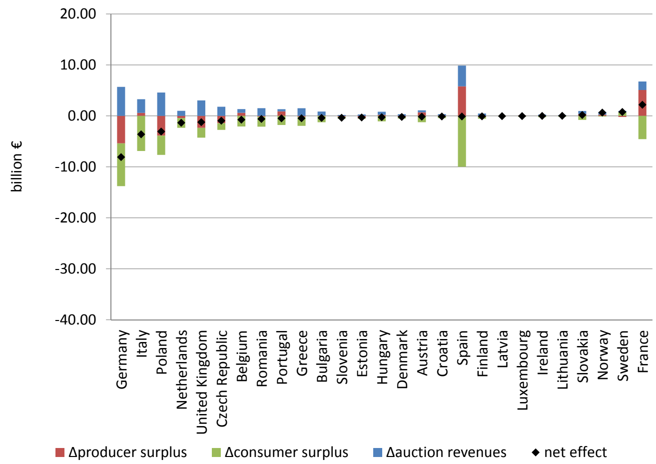
4.3 MSR and price floor interaction

In this section, we examine the interaction of the novel MSR cancellation provision and minimum prices. We examine the role of minimum prices as (imperfect) substitutes for quantitative allowance cancellations. To that end, we analyze additional hypothetical cases without the MSR cancellation provision, and compare them with the combined effects of the two measures.

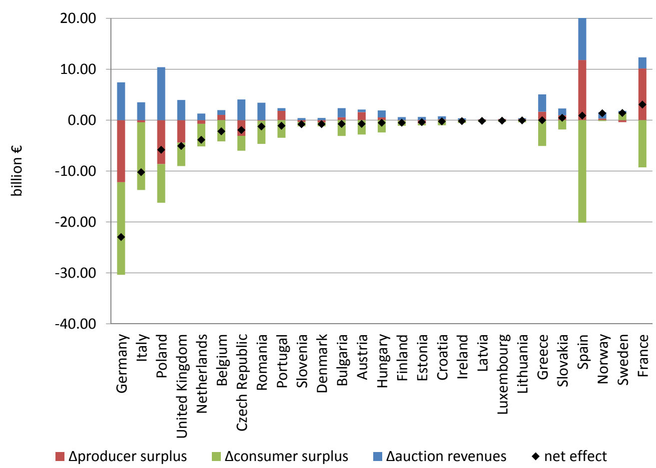
The horizontal axis in figure (4.6) describes the cumulative emissions reductions indexed to zero in a baseline scenario without MSR cancellation, but including member state actions, which we call scenario B2 (w/o MSR). The red line shows the incremental effect of the MSR cancellation. Although the MSR allowances are canceled only in 2023 (see section (3.2)), the effect on emissions is strongest between 2035 and 2045. This is because the MSR-only scenario partly reduces the allowance surplus, but a considerable amount of allowances remains in the bank (see part (b) in figure (4.1)). Nonetheless, the reduction in the size of the bank causes withdrawals from the bank to decline more quickly and the bank to be exhausted earlier. Additional early abatement (2020-2030) effects due to the MSR are triggered by the anticipated future scarcity, which is reflected by a somewhat higher CO2 price (see red lines in figure (4.7)). Intuitively, additional abatement equals the assumed amount of allowances canceled from the MSR (1,030 Mt CO2, associated with the electricity sector portion of the ETS; see section (3.2)).

Figure 4.5: Wealth effects due to reserve price set by coalition (S2)

(a) reserve price: 15€



(b) reserve price: 25€



note: the figure shows the difference between the policy scenario with the respective reserve price and baseline scenario B2. The numbers are the to 2015 discounted sums.

In comparison to the MSR scenario, a minimum price at the considered levels leads to considerably higher cumulative additional mitigation. Also, the reductions are always achieved earlier than with the MSR cancellation. This is shown by the solid blue and green lines in figure (4.6). With a price floor of 15 €/t the level of emissions savings achieved by the MSR in 2045 is reached by 2035; and with a price floor of 25 €/t this level of emissions savings is already achieved in the early 2020s. This outcome is triggered by the different allowance price levels of these two measures, as shown in figure (4.7).

As a thought experiment, we now turn to the effect of the novel MSR cancellation provision comparing it to the situation where only a minimum price would be in place (and no MSR cancellation). The dashed lines in figure (4.6) indicate that in this case the incremental effect of the fixed MSR deletion (again 1,030 Mt CO2) is relatively weak: For a 25 € price floor, there is little additional abatement in 2025, and the CO2 price is somewhat higher only in 2025 (compare solid and dashed green lines in figure (4.7)). The reason for this weak additional MSR effect is that a large part of the MSR deletion is offset by less allowances withholdings through the reserve prices. This highlights that reserve price floors and the MSR are partly substitutes due to the duality of prices and quantities in emission mitigation. Note that with a reserve price, it is likely that there also would be less MSR deletion and therefore the substitution effect would be even stronger if the MSR deletion was endogenous in our model.

In the context of our model the MSR can be conceived as an implicit price floor that is dual to the MSR and yields the same emissions outcome. Given that in any model period the CO2 price is a negative function of the bank level and the MSR deletion is triggered by the bank level, there is an implicit price floor that would trigger allowance deletion equivalent to that achieved by the MSR. Put differently, the allowance supply is already to some degree price elastic to the MSR. However, a major difference between the implicit price floor of the MSR and the explicit price floor is that the MSR's implicit price floor is difficult to estimate because the relation between bank level and CO2 price can be different in each year. An explicit reserve price has the advantage that the supply reaction in response to changing prices is contemporaneous, easy to establish and thus also to predict.

4.4 Sensitivities

In this section, we briefly discuss the differences between the cases in which the reserve price is set by all EU ETS member states (scenario S1) instead of only a coalition (S2, see above). . The coalition is always able to achieve the targeted price floor by withholding allowances that is achieved when the price floor is introduced by all member states. Therefore, consumer and producer surplus changes are identical in S1 and S2 scenarios, and only the change in auction revenues differs between member states. By inspecting figures (4.5) and (4.8), one observes that the auction revenues in scenarios S1 when the price floor is introduced by all member states are larger compared to S2 for states that have a reserve price in S2, and lower for the other states. That is, because the forgone revenues due to a lower number of auctioned allowances is distributed over more states, the states that were harmed the most under the price floor coalition like Germany and Italy fiscally benefit the most if all states set a price floor. Germany, for example, receives 1.7 and 5.7 bn. € higher auction revenues in cumulative terms (and thus also higher net effects) under the 15 € and 25 € price floors, when the price floors are set by all states.

Figure 4.6: Cumulative emission savings compared to B2 (w/o MSR)

Note: the figure shows the difference between cumulative emissions in scenario B2 without the MSR cancellation and the respective scenario. For example, the red line is,B2 (w/o MSR) - B2, the straight blue line is B2 (w/o MSR) - B2_S2_15 (w/o MSR) and the dashed blue line is B2 (w/o MSR) - B2_S2_15.

5 Conclusions

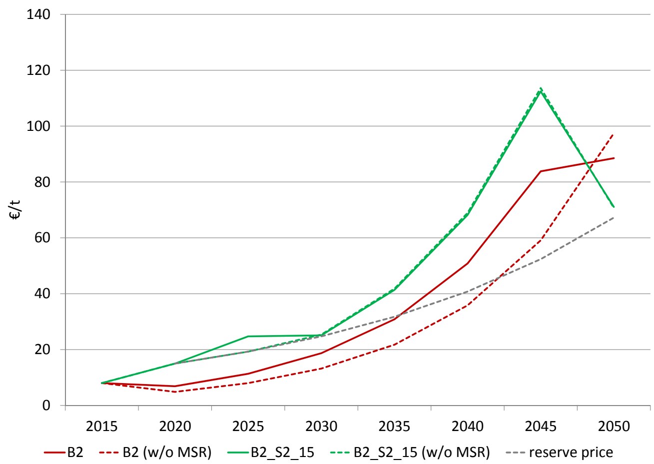
In this paper we have analyzed the price and welfare effects of a minimum price in the EU ETS, implemented to remedy the waterbed effect that results from overlapping national policies. We find that national coal phaseout policies in the Power Past Coal Alliance members states plus Germany considerably reduce the allowance price. Without such policies allowance prices are above 40 €/t in 2030, falling to 20 €/t because of the coal phase out policies. The phase out currently under debate in Germany is particularly important for the size of this effect because the country has by far the highest coal emissions of all the member states taking such action.

By design, a minimum price can mitigate this drop in prices. The different minimum price levels we consider (15 €/t and 25 €/t starting in 2020) lead to different price paths because of their initial level in 2020 and because we assume the minimum price rises at 5%/a, whereas the discount rate rises at 10%. However, the shape of the price path induced by the 25 €/t minimum price closely resembles the baseline. As a consequence of the minimum prices, 1.6 Gt of allowances associated with the electricity sector portion of the ETS are withheld from circulation under the 15 €/t scenario, and 3.9 Gt are withheld under the 25 €/t scenario. These quantities are in addition to the 1,030 Mt (electricity sector portion) of allowances that will be canceled via the MSR 2023 in line with the recent EU ETS reform. Thus, the relative contribution of the MSR cancellations is small in comparison, yet it positively interacts with the minimum price by reducing the amount of withheld allowances through the reserve price. However, the price effect of the MSR is harder to understand and predict, and ease of implementation and administration (transparency and predictability) appears simpler under a minimum price.

The introduction of a minimum price creates both winners and losers. In absolute terms, Germany, Italy and Poland incur the highest losses, while France gains most. The main reason making France a winner is the already relative clean energy mix of the country, implying a rather

Figure 4.7: CO2 prices for different MSR assumptions

(a) reserve price: 15€



(b) reserve price: 25€

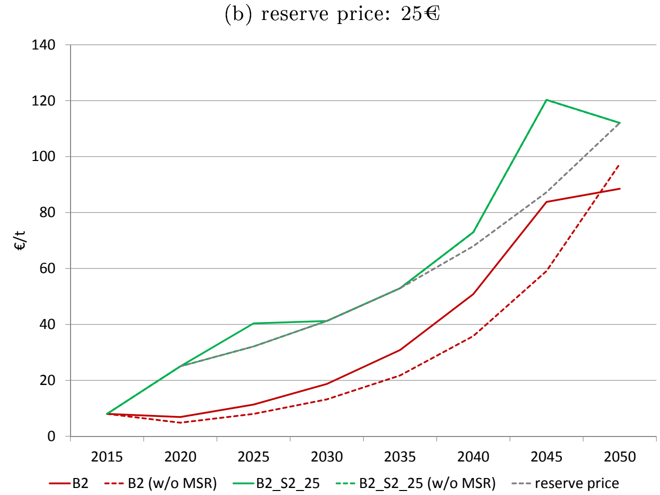
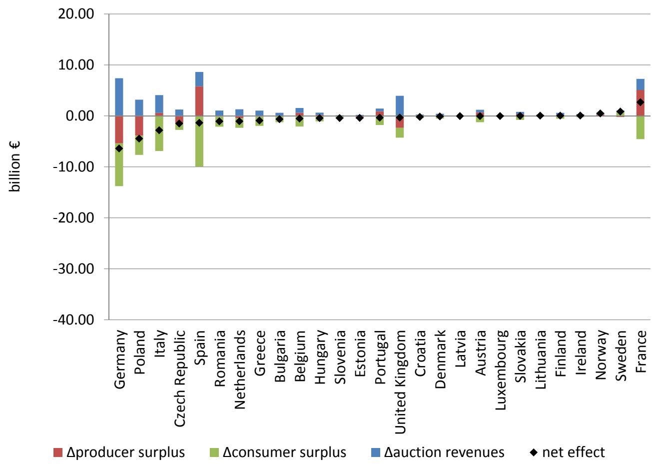
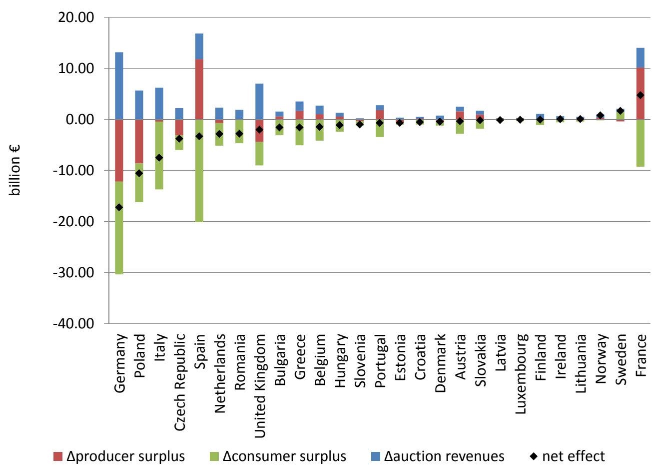


Figure 4.8: Wealth effects due to reserve price set by all EU ETS countries (S1)

(a) reserve price: 15€



(b) reserve price: 25€



note: the figure shows the difference between the policy scenario with the respective reserve price and baseline scenario B2. The numbers are the to 2015 discounted sums.

small cost of compliance. The primary effect of higher CO2 prices is higher electricity prices, which imply transfers from consumers to producers. The opposite holds for Germany, Poland and Italy, which all have a relatively high share of coal in their power systems. The relative outcomes among these countries does not change under the different minimum price levels, and Germany's loss of 23 bn. € (cumulative through 2050) under a 25 €/t minimum price constitutes the upper end of the scale. Though large, this value is about the same amount the country pays for renewable support each year(~24 bn. € in 2016). Further, though not analyzed here, it is likely that a higher allowance price would reduce renewable support costs, implying additional benefits. Accordingly, the incentives for Germany to adopt a minimum price might actually be more favorable than the net welfare effect we calculate. However, such additional benefits might be less relevant in the cases of Italy and especially Poland, and thus additional transfers or compensations might be needed to bring these countries on board. One important lever for providing compensation is the apportioning of allowances. In that regard, the welfare analysis reveals that in all cases the positive inframarginal price effect dominates the negative volume effect and auction revenues increase for all countries. In face of the distributional effects of a minimum price, countries like Poland and Italy that realize unfavorable outcomes could be apportioned higher shares from the overall allowance budget, which might be implemented at the expense of winning countries. As mentioned above, respective bargaining has already been observed in past EU ETS reforms, and could be informed by this analysis.

Finally, there are additional aspects not considered in this work deserving more analysis in future research. First, the interaction of the MSR and a minimum price is more complex than assumed in our model, and the actual quantity of canceled allowances depends on a number of additional factors including the temporal patterns of emission reductions and banking. To better account for this, the model could be coupled with dedicated spreadsheet models that fully cover the mechanistic details of the MSR. Doing so would also enable analysis of the impact of alternative MSR thresholds, which obviously lead to discontinuities that could have significant impacts on cancellations. Second, the analysis of distributional effects could be extended to consider effects on different producers (technologies) within a country. Such an analysis could for example shed light on potential gains for renewable producers in Germany, which in turn would reduce support costs as mentioned above. Third, it is important to better understand the temporal patterns of the impacts, especially because of the near term government budget implications from changing auction revenues. A higher level of accuracy for respective estimates might be essential information required by finance ministers. Fourth, if a minimum price is also introduced with the intention to address regulatory uncertainty regarding a potential retrospective softening of the cap, a different kind of analysis is needed. More precisely, the assumption of perfect foresight in the model would need to be replaced with a stochastic framework. Such an analysis would be important to better understand and quantify the value of "early action" effects of a minimum price to address the problem of long-term credibility of commitments in climate policy.

References

Bang, G., Victor, D. G., and Andresen, S. (2017). California's Cap-and-Trade System: Diffusion and Lessons. *Global Environmental Politics*, 17(3):12–30.

Baumol, W. J. and Oates, W. E. (1988). *The Theory of Environmental Policy*. Cambridge University Press, 2nd edition.

Bel, G. and Joseph, S. (2015). Emission abatement: Untangling the impacts of the EU ETS and the economic crisis. *Energy Economics*, 49:531–539.

Burtraw, D., Holt, C., Palmer, K. L., Paul, A., and Shobe, W. (2018). Quantities with Prices. RFF Working Paper. Technical report.

Burtraw, D. and McCormack, K. (2017). Consignment auctions of free emissions allowances. *Energy Policy*, 107:337–344.

Burtraw, D., Palmer, K., and Kahn, D. (2010). A symmetric safety valve. *Energy Policy*, 38(9):4921–4932.

Calel, R. and Dechezleprêtre, A. (2016). Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Review of Economics and Statistics*, 98(1):173–191.

Capros, P., Mantzos, L., Parousos, L., Tasios, N., Klaassen, G., and Van Ierland, T. (2011). Analysis of the EU policy package on climate change and renewables. *Energy Policy*, 39(3):1476–1485.

CARB (2011). Final Supplement to the AB 32 Scoping Plan Functional Equivalent Document. Technical report.

Chichilnisky, G. and Heal, G. (1994). Who should abate carbon emissions? *Economics Letters*, 44(4):443–449.

Convery, F. J. (2008). Reflections–The Emerging Literature on Emissions Trading in Europe. *Review of Environmental Economics and Policy*, 3(1):121–137.

Delbeke, J., Klaassen, G., van Ierland, T., and Zapfel, P. (2009). The role of environmental economics in recent policy making at the European Commission. *Review of Environmental Economics and Policy*, 4(1):24–43.

Dorsch, M., Flachsland, C., and Kornek, U. (2018). Enhancing Climate Policy Ambition Using Strategic Transfers: Allowance Allocation and Revenue Spending in the EU ETS. Mimeo. Technical report.

EC (2015). Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments. SWD(2015) 136 final. Technical report.

EC (2018). Directove 2018/410 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814. Technical report.

Edenhofer, O., Flachsland, C., Wolff, L. K., Schmid, A., Leipprand, A., Koch, N., Kornek, U., and Pahle, M. (2017a). Decarbonization and EU ETS Reform: Introducing a price floor to drive low-carbon investments. MCC Policy Paper. Technical report.

Edenhofer, O., Roolfs, C., Nahmacher, P., Gaitan, B., and Flachsland, C. (2017b). Agreeing on an EU ETS minimum price to foster solidarity, subsidiarity and efficiency in the EU. In *Energy Tax and Regulatory Policy in Europe: Reform Priorities, edited by Ian Parry, Karen Pittel, and Herman Vollebergh*. MIT Press.

Ellerman, A. D., Marcantonini, C., and Zaklan, A. (2016). The European Union Emissions Trading System: Ten Years and Counting. *Review of Environmental Economics and Policy*, 10(1):89–107.

FANKHAUSER, S., HEPBURN, C., and PARK, J. (2010). COMBINING MULTIPLE CLIMATE POLICY INSTRUMENTS: HOW NOT TO DO IT. *Climate Change Economics*, 01(03):209–225.

Fell, H., Burtraw, D., Morgenstern, R. D., and Palmer, K. L. (2012). Soft and hard price collars in a cap-and-trade system: A comparative analysis. *Journal of Environmental Economics and Management*, 64(2):183–198.

Fischer, C. (2018). The Legal and Economic Case for an Auction Reserve Price in the EU Emissions Trading System. Mimeo. Technical report.

Fuss, S., Flachsland, C., Koch, N., Kornek, U., Knopf, B., and Edenhofer, O. (2018). An assessment framework for intertemporal economic performance of cap-and-trade systems: lessons from the EU ETS. in press. *Review of Environmental Economics and Policy*.

Goulder, L. H. and Stavins, R. N. (2011). Challenges from State-Federal Interactions in US Climate Change Policy. *American Economic Review*, 101(3):253–257.

Hepburn, C., Neuhoff, K., Acworth, W., Burtraw, D., and Jotzo, F. (2016). The economics of the EU ETS market stability reserve. *Journal of Environmental Economics and Management*, 80:1–5.

IPCC (2014). Summary for Policymakers. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler,*, pages 1–33.

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, 54(2-3):164–174.

Joas, F., Pahle, M., Flachsland, C., and Joas, A. (2016). Which goals are driving the Energiewende? Making sense of the German Energy Transformation. *Energy Policy*, 95:42–51.

Kling, C. and Rubin, J. (1997). Bankable permits for the control of environmental pollution. *Journal of Public Economics*, 64(1):101–115.

Martin, R., Muûls, M., and Wagner, U. J. (2016). The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years? *Review of Environmental Economics and Policy*, 10(1):129–148.

Meckling, J., Kelsey, N., Biber, E., and Zysman, J. (2015). Winning coalitions for climate policy. *Science*, 349(6253):1170–1171.

Newell, R., Pizer, W., and Zhang, J. (2005). Managing Permit Markets to Stabilize Prices. *Environmental & Resource Economics*, 31(2):133–157.

Nordhaus, W. (2015). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, 105(4):1339–1370.

Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., and Zysman, J. (2017). What Stands in the Way Becomes the Way. Sequencing in Climate Policy to Ratchet Up Stringency Over Time. RFF Report. Technical report.

Perino, G. (2018). New EU ETS Phase 4 rules temporarily puncture waterbed. *Nature Climate Change*, 8(4):262–264.

Pizer, W. A. (2002). Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics*, 85(3):409–434.

Roberts, M. J. and Spence, M. (1976). Effluent charges and licenses under uncertainty. *Journal of Public Economics*, 5(3-4):193–208.

Salant, S. W. (1983). The Vulnerability of Price Stabilization Schemes to Speculative Attack. *Journal of Political Economy*, 91(1):1.

Schwerhoff, G., Kornek, U., Lessmann, K., and Pahle, M. (2018). LEADERSHIP IN CLIMATE CHANGE MITIGATION: CONSEQUENCES AND INCENTIVES. *Journal of Economic Surveys*, 32(2):491–517.

Weigt, H., Ellerman, D., and Delarue, E. (2013). CO2 abatement from renewables in the German electricity sector: Does a CO2 price help? *Energy Economics*, 40:S149–S158.

Williams, R. C. (2012). Growing state-federal conflicts in environmental policy: The role of market-based regulation. *Journal of Public Economics*, 96(11-12):1092–1099.

Wood, P. J. and Jotzo, F. (2011). Price floors for emissions trading. *Energy Policy*, 39(3):1746–1753.

World Bank (2017). State and Trends of Carbon Pricing. Technical Report November.