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# Endogenizing the cap in a cap-and-trade system: Assessing the agreement on EU ETS phase 4

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**Working Paper 2018:2**

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# Endogenizing the cap in a cap-and-trade system: Assessing the agreement on EU ETS phase 4[1]

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**Abstract:**
In early 2018, a reform of the world's largest functioning greenhouse gas emissions cap-and-trade system, the EU Emissions Trading System (ETS), was formally approved. The reform changes the main principles of the system by endogenizing the previously fixed emissions cap. We show that the effective emissions cap is now affected by the allowance demand and therefore not set directly by EU policymakers. One consequence of this is that national policies that reduce allowance demand can reduce long-run cumulative emissions, which is not possible in a standard cap-and-trade system. Using a newly developed dynamic model of the EU ETS, we show that policies reducing allowance demand can have substantial effects on cumulative emissions. Our model simulations also suggest that the reform reduces aggregate emissions in both the short and long run, but the long-run impact is substantially larger. Yet, the reform has a small impact on the currently large allowance surplus.

**Keywords:** Cap-and-trade, EU ETS, Market stability reserve, Overlapping policies
**JEL:** Q48, Q54, Q58

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[1] This working paper is partly based on Beck and Kruse-Andersen (2018). Some of the conclusions also appear in the Danish report "Economy and Environment, 2018" from the Chairmen of the Danish Economic Council of Environmental Economics published in February 2018. We would like to thank Lars Gårn Hansen, Thomas Bue Bjørner, Louis Birk Stewart, Peter Birch Sørensen, and Frederik Silbye as well as seminar participants at the Technical University of Denmark, the Danish Ministry of Energy, Utilities and Climate, the Danish Energy Agency, and the Department of Food and Resource Economics, University of Copenhagen for comments, discussions, and suggestions. Any remaining errors are our own.

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# 1 Introduction

The EU Emissions Trading System (ETS) is the world's largest functioning greenhouse gas emissions cap-and-trade system (European Commission, 2017a). It covers large energy-intensive installations like power plants and cement production facilities. The aim of the EU ETS is to cost-efficiently reduce emissions from covered installations across the EU. Alongside the EU ETS, many EU countries implement national policies, which also aim to reduce greenhouse gas emissions (European Environment Agency, 2015). Such policies include subsidies for renewable energy and electrification. Very often, these policies overlap with the EU ETS, in the sense that they reduce demand for emission allowances. It is well understood how such overlapping policies interact with the long-run outcome of a standard cap-and-trade system: since national policies do not affect the total amount of allowances available over the lifetime of the system, cumulated emissions are unchanged.[2]

In February 2018, the EU adopted a new reform of the EU ETS (European Parliament, 2018). We show that a consequence of the reform is that, under some circumstances, cumulated emissions are no longer exogenous to overlapping national policies. Thus, the reform changes one of the fundamental principles of a cap-and-trade system, namely that that the emissions cap is directly controlled by the policymakers.

This fundamental change is a result of changes to the rules of the so-called Market Stability Reserve (MSR).[3] The MSR absorbs allowances when the allowance surplus (amount of unused allowances in circulation) is large and releases allowances, when the allowance surplus is small.[4] Before the reform, the MSR could affect the intertemporal availability of allowances but not the total amount of allowances. The reform introduces a cap over the stock of allowances that can be held in the MSR. When this cap is binding, any additional allowances that are taken into the MSR are cancelled. This reduces the total amount of allowances in the system. Since the uptake of allowances into the MSR depends on the amount of allowances in circulation, the reform implies that national policies can result in additional allowance cancellations within the MSR by af-

[2] This effect is often referred to as the waterbed effect, and it is well established in the cap-and-trade literature. However, national policies could affect long-run emissions through the EU ETS negotiations. Yet, it is difficult to verify this effect, and it is especially difficult to establish a causal link between a particular national policy and an EU ETS negotiation outcome. In addition, small changes in allowance demand might not affect the negotiation outcome.

[3] The MSR was originally conceived as a way to address the large allowance surplus and strengthen the resilience of the system to major demand shocks (European Commission, 2017a).

[4] The allowance surplus is basically the amount of banked allowances available to the market. More precisely, the allowance surplus is given by the allowance supply minus the allowance demand (primarily surrendered allowances) minus the stock of allowances in the MSR.

fecting the allowance demand. Thus, national policies that overlap with the EU ETS can, under these circumstances, result in a reduction in the amount of allowances available to the market in the long run, which effectively lowers the emissions cap.

We study the consequences of the recent EU ETS reform both qualitatively and quantitatively. The quantitative analysis is especially interesting, as the effect on the impact of national policies only comes about if the allowance surplus continues to be large over the coming years and if the MSR cap is binding. To examine these quantitative issues, we develop a dynamic model of the EU ETS. The model is calibrated to match the developments of the EU ETS before the latest reform. The idea is to present a plausible forecast to illustrate likely consequences of the reform.

Our quantitative analysis focuses on both the aggregate impact of the reform and the implications for national climate policies that overlap with the EU ETS. The results suggest that the reform reduces both short-run and long-run aggregate emissions. Yet the reform has a significantly larger effect on the long-run emission. Specifically, the results suggest that long-run cumulative EU ETS emissions are reduced by about 14 pct., while the reduction is less than 3 pct. until 2030. The reform also increases the allowance price, as it increases the allowance scarcity at all points in time. Yet, the reform has a rather small impact on the currently large allowance surplus over the coming years.

Regarding national policies, the results suggest that the timing of these policies is crucial for their long-run impact on aggregate emissions. Policies that reduce allowance demand are more effective if they are implemented fast, while the opposite is true for policies that reduce allowance supply through allowance cancellations.

Besides the results of the combined qualitative and quantitative analysis, the present study contributes to the existing literature in at least two ways. Firstly, the model developed below is calibrated using a novel calibration procedure, which ensures that the model is able to match historical emission patterns of the sectors covered by the EU ETS as well as the EU ETS market situation before the recent reform. Secondly, the model features a technological component, which captures the anticipated catch-up of renewable relative to fossil fuel-based technologies. This catch-up of renewable technologies is assumed relatively faster at the beginning of the period, which reflects that the development of renewable technologies slows down as renewable technologies mature. Other comparable studies either do not feature a similar component – thereby essentially eliminating the role of technological catch-up of renewable energy sources – or they assume that the catching-up effect is not weakened over time.

This paper is related to several studies in the EU ETS literature, and, in particular, studies investigating issues related to the MSR. One strand of literature investigates the MSR as a stabilization mechanism (Richstein et al. 2015; Perino and Willner 2016; Fell 2016). Fell (2016) finds that the MSR fulfills its originally intended purpose and is price stabilizing, while Richstein et al. (2015) and Perino and Willner (2016) find that the MSR might increase price volatility. The studies mentioned here do not examine the effects of the latest reform.

There are to the best of our knowledge four studies that are more closely related to the present paper. Firstly, Perino and Willner (2017) investigate three reform proposals for the EU ETS, one of which includes the key change to the MSR that this paper focuses on. However, key assumptions made by the authors about the rate of technological change and firm discounting rates mean that the MSR cap only becomes binding for a short period of time, and the effect described above is therefore only relevant in a short time span. In contrast, we show that the MSR cap can be binding over several decades under plausible assumptions. Furthermore, the authors do not explicitly consider the interplay between the EU ETS reform and national policies that reduce allowance demand.

Secondly, Perino (2018) discusses the implications of the recent EU ETS reform. His main points are largely in line with our conclusions. The analysis of Perino (2018) draws in part on the simulation results from Perino and Willner (2017) and the same differences in assumptions as those described above are therefore present. In addition, Perino (2018) computes the mechanical effects on long-run aggregate EU ETS emissions of abating one tonne of emission at different points in time without considering the effect of the policy on allowance prices. We go one step further by computing the effect on long-run aggregate EU ETS emissions of national policies using a dynamic model. This ensures that the direct effect of the policy is diminished through the effect on the allowance price of a reduction in allowance demand. In line with the present study, Perino (2018) finds that abating sooner rather than later has a larger impact on long-run emissions.

Thirdly, the Swedish National Institute of Economic Research (2018) analyzes how the recent EU ETS reform affects national climate policies. Similar to this paper, their study includes model simulations based on a dynamic model of the EU ETS. In contrast to the model used in this paper, the simulations of the National Institute of Economic Research (2018) do not take technological advances into account. This means that the emission level is constant over time in the absence of the EU ETS. In addition, the demand side in their model is represented by a single firm, which takes its own effects on the allowance allocations into account when optimizing allowance consumption. In this paper, the demand side is also represented by a single firm, but this firm does not take the effects of its own actions on the allowance allocations into account when optimizing allowance consumption. We believe that the approach taken in this paper is more realistic, as each firm represented by the representative firm has a very small influence on the aggregate variables governing the system. Each individual firm will, therefore, take the allowance allocations as given, and therefore the representative firm will do the same. As a consequence of the different approaches, the National Institute of Economic Research (2018) finds that the introduction of the MSR cap increases emissions in the short run, while the MSR cap reduces short-run emissions in our analysis.

Finally, Silbye and Sørensen (2017) investigate the impact of national policies in sectors covered by the EU ETS in a dynamic model under the pre-reform rules. However, their model has also been used to model the MSR cap introduced by the latest EU ETS reform which resulted in findings similar to those in the present study (see Danish Council on Climate Change, 2017). In contrast to the framework of Silbye and Sørensen (2017), this paper builds on a micro-founded model, while it is not explicitly shown how the optimality conditions in the model developed by Silbye and Sørensen (2017) are derived.[5] Moreover, the authors assume exponential technological growth in renewable technologies relative to fossil fuel-based technologies. This may exaggerate the potential scope for renewable energy technologies.[6] In the present paper, the technological growth rate is calibrated from historical data, and it is assumed that the catching-up effect is weakened over time as renewable energy technologies catch up to the mature technologies based on fossil fuels.

This paper is organized as follows. Section 2 describes the EU ETS and goes into more detail about the long-run effects of national policies before and after the reform in a simple setup. The formal model is presented and calibrated in section 3, while results in section 4 quantify the qualitative effects discussed in section 2. A robustness analysis is provided in section 5, and section 6 concludes.

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[5] It can be shown that the model developed by Silbye and Sørensen amounts to the first-order conditions of a special case of the general model presented below (see Beck and Kruse-Andersen, 2018).

[6] Rootzén and Johnsson (2013, 2015) find that it will be difficult to meet ambitious emission targets for petroleum refineries, iron and steel plants, and cement producers in the absence of major breakthrough technologies like effective carbon capture and storage.

## 2 The EU ETS and long-run effects of national policies

This section first presents the general characteristics of the EU ETS and the recent reform. Subsequently, it is discussed how overlapping climate policies by EU member states affect aggregate emissions in the EU ETS before and after the recent reform.

### 2.1 An overview of the pre-reform system

Firms covered by the EU ETS must hand in one (emission) allowance for each tonne of $CO_2$-equivalent greenhouse gases emitted.[7] The EU issues new allowances every year and these allowances are partly auctioned and partly allocated for free to firms covered by the EU ETS. In 2013, the EU issued just over 2 billion allowances. Since then, the yearly issuances have been reduced by about 38.3 m. allowances per year.

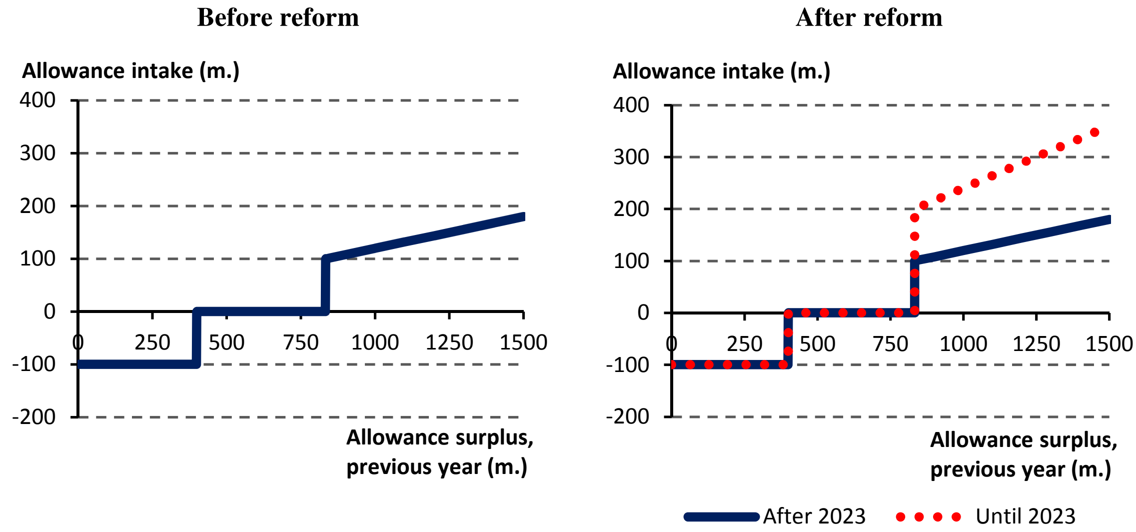
Since 2008, it has been possible to bank allowances for future use, and this has been extensively practiced over the last years, resulting in a large allowance surplus. The large allowance surplus has been seen as problematic by several actors including the EU itself. The EU has therefore tried to reduce the surplus through different measures. One of these measures is the MSR.

The legal background for the MSR was introduced in 2015, but the reserve will not operate until 2019 (EU, 2015). The rules for MSR intake and release are illustrated in the left panel of figure 1. If the allowance surplus of the previous year is below 400 m., 100 m. allowances are taken from the MSR and auctioned to firms in the ETS sector. There is no change in the stock of allowances in the MSR, if the allowance surplus of the previous year is between 400 and 833 m. Finally, if the allowance surplus of the previous year is above 833 m., newly issued allowances corresponding to 12 pct. of the allowance surplus of the previous year are moved to the MSR. These allowances are taken from the pool of newly issued allowances auctioned by the member states.

Note that under the pre-reform rules, the MSR does not affect the amount of allowances in the system. Yet the MSR can affect the intertemporal availability of allowances.

[7] For ease of reading, we will use the shorthand "$CO_2$" to refer to $CO_2$-equivalents in the remainder of the paper.

*Figure 1. Rules for intake and release of allowances in the Market Stability Reserve*




Source: EU (2015, 2018).

## 2.2 The main elements of the recent reform[8]

The recent reform changes the EU ETS in three important ways. Firstly, the reform increases the linear reduction of newly issued allowances from about 38.3 to 48.4 m. allowances per year.[9] If this linear reduction continues indefinitely, the EU will issue the last allowances in 2057.

Secondly, the reform increases the MSR intake rate to 24 pct. until 2023. The right panel of figure 1 illustrates the MSR rules after the reform.

Finally, the reform introduces a cap over emission allowances held in the MSR. Allowances exceeding this cap are cancelled. The cap is equal to the auctioning volume of the previous year, i.e., if there are 2 billion allowances in the MSR and 1.5 billion allowances were auctioned the year before, then 0.5 billion allowances in the MSR are cancelled due to the MSR cap. The reform also implies that 57 pct. of the newly issued allowances are auctioned from 2021, and thus, as the annual amount of newly issued allowances decreases systematically over time, so does the MSR cap.

The increase in the annual reduction of newly issued allowances as well as the change to the intake rules of the MSR, while important in their own right, do not change the basic principles of the allowance system: the total amount of issued allowances over the

[8] The legal background of the reform is EU (2018).

[9] This is often referred to as an increase in the linear reduction factor from 1.74 to 2.2 pct. The amount of allowances reduced is calculated as the linear reduction factor multiplied with the average yearly amount of newly issued allowances over the period 2008-12.

lifetime of the system (cumulated supply of allowances) are equal to the total amount of allowances that can be used for emissions (the cumulated emissions cap). Since all allowances stored in the MSR are eventually released, the cumulated emissions cap is still set by the cumulated supply of allowances. Thus, the maximum long-run quantity of pollution emission is determined directly by the system designers. However, the introduction of the MSR cap means that national policies can now reduce the cumulated emissions cap below the cumulated supply of allowances. Such policies might therefore reduce the effective emissions cap. The two following subsections describe this effect in more detail.

### 2.3 Effects of overlapping policies before the reform

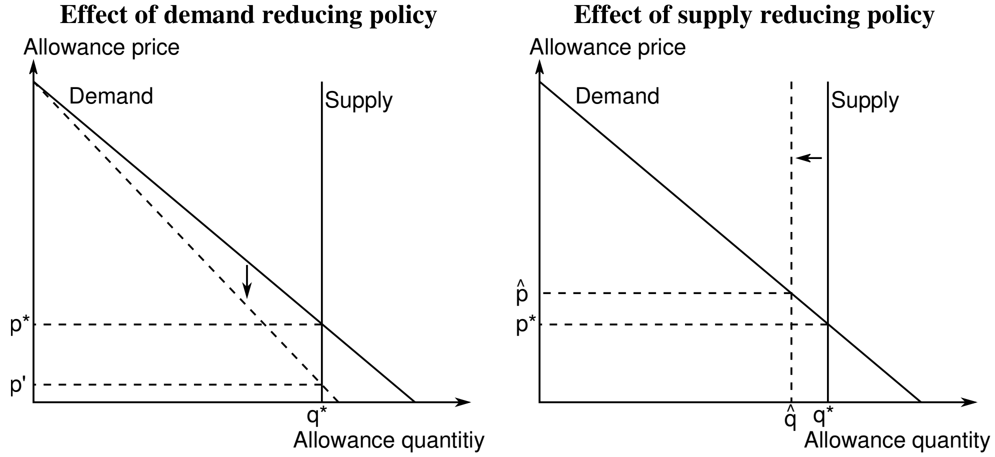
In the following, we consider only the long-run effects of national policies that overlap with the EU ETS. The long-run market equilibrium before the reform is illustrated in figure 2. The cumulated supply of allowances is fixed by EU policymakers and the demand for allowances is decreasing in the allowance price.[10]

The left panel of figure 2 shows a situation where an EU member state implements a policy that reduces the demand for allowances. This policy could be subsidies to renewable energy sources, subsidies to energy efficiency improvements, a national carbon tax in the ETS sector, or taxes on private power consumption. The policy reduces domestic demand for allowances. But since the allowance supply is fixed, the policy reduces the allowance price, and the demand for allowances is unaffected at the EU level. Consequently, policies that curb allowance demand have no effects on long-run emissions. This type of overlapping climate policy is therefore ineffective under the pre-reform EU ETS rules: it reduces the effectiveness of the EU ETS while it does not affect aggregate emissions.

The right-hand side of figure 2 shows a situation where an EU member state cancels a quantity of allowances. The policy reduces the supply of allowances at the EU level, resulting in an increase in the allowance price. As the long-run emission equals the amount of available allowances, the policy reduces long-run emissions at the EU level.

[10] It is assumed in figure 2 that the long-run emissions cap is binding in the pre-reform scenario, resulting in a positive allowance price.

*Figure 2. Long-run equilibrium of the EU ETS before the reform and the effects of overlapping policies*




Note: Before additional policy interventions, the equilibrium allowance price is $p^*$ and the equilibrium allowance demand is $q^*$. The demand reducing policy decreases the equilibrium price from $p^*$ to $p'$, while it does not change the equilibrium demand. The supply reducing policy reduces the allowance supply from $q^*$ to $\hat{q}$, where the latter quantity also equals the equilibrium demand. The policy also increases the equilibrium price from $p^*$ to $\hat{p}$.

## 2.4 Effects of overlapping policies after the reform

After the reform, policymakers still determine an emissions cap. However, a policy that reduces demand for allowances will reduce short-run allowance demand. This increases the allowance surplus and thereby the amount of allowances absorbed by the MSR. If the MSR cap is binding, the reform also results in allowance cancellations, and the demand policy will effectively reduce long-run emission at the EU level. Thus, the reform makes demand-reducing policies more effective when seen from an environmental perspective.[11]

Symmetrically, policies that increase allowance demand have the opposite effect. They decrease the allowance surplus and thereby the amount of allowances absorbed by and cancelled in the MSR. Such policies include subsidies to electric cars, which move emissions from the non-ETS sector into the ETS sector.

In addition, the reform might reduce the effectiveness of policies that reduce allowance supply, such as an allowance cancellation policy. Allowance cancellations have two counteracting effects on long-run allowance supply. On the one hand, cancelling one

[11] An element left out of this discussion is the environmental impact of the timing of emissions. If emissions are discounted, supply reducing policies that effectively postpone some emissions without reducing cumulated emissions may be preferable from an environmental perspective. In this sense, national policies that reduce emission demand today can have a positive environmental effect. The timing effects of national policies can be amplified by the MSR under the pre-reform rules as emphasized by Silbye and Sørensen (2017). In this paper, we focus on the effects of national policies on the flows of emissions over time. In this way, we sidestep a discussion of what a reasonable discounting rate on emissions may be.

million allowances reduces the allowance supply directly by one million allowances. On the other hand, the cancellation policy reduces the amount of allowances available to the market and thereby the allowance surplus. This reduces the amount of allowances absorbed by the MSR. If the MSR cap is binding, the long-run effectiveness of the allowance cancellation policy is partly counteracted by a reduction in the amount of allowances cancelled in the MSR.

The discussion of national policies after the recent reform assumes that the allowance surplus is so large that a larger allowance surplus means that more allowances are taken into the MSR. However, this is not always true. When the allowance surplus is small, national policies have the same effects as before the reform. This is because the MSR does not absorb additional allowances and the effects described above do not occur.

The date where the allowance surplus is below the intake threshold (833 m. allowances) is referred to as the cut-off date. National demand policies that are in effect after this cut-off date have a weaker effect on long-run aggregate emissions. Establishing a new wind farm can, for instance, reduce allowance demand several years before and several years after the cut-off date, but only the demand reductions before the cut-off date results in additional allowances being placed in the MSR. Thus only demand reductions occurring before the cut-off date can lead to additional allowance cancellations within the MSR. In contrast, the effect of the cancellation policy on long-run aggregate emissions can become weaker, when cancellations are conducted before the cut-off date. This is because an allowance cancellation policy occurring before the cut-off date reduces the allowance surplus and thereby the amount of allowances absorbed by and potentially cancelled in the MSR.

At this point, it is clear that the reform can affect the effectiveness of national policies that affect either demand for or supply of allowances. This means that the effective aggregate emissions cap is not directly determined by the policymakers who decide the yearly allowance issuances.  In addition, it should also be clear that the effects of both types of national policies depend on several other variables: the allowance surplus, the stock of allowances in the MSR, and the MSR cap. In the following section, a model is developed, which takes all of these variables into account.

## 3 Model

The model is designed to forecast the general trends in the $CO_2$ emissions, the allowance surplus, the stock of allowances in the MSR, and the allowance price in the EU ETS. Firms in the EU ETS are forward looking to ensure a realistic response to policy changes. Only stationary installations are modeled which covers about 97 pct. of the $CO_2$ emissions covered by the EU ETS (European Environment Agency, 2017b).[12]

The effect of the reform is computed as the deviation to the pre-reform scenario. In the pre-reform scenario, the MSR is governed by the pre-reform rules. In addition, the pre-reform scenario includes the increase in the linear reduction rate of newly issued allowances from 2021.[13] Hence, the difference between the pre-reform and post-reform scenarios boils down to the rule changes for the MSR.

## 3.1 Overview

The model is formulated in discrete time with the time index: $t = 1,2, \dots, T$. The first period ($t = 1$) represents the year 2017. The model is set to run until 2125 ($T = 109$), as all allowances are used before this year in all considered scenarios. The model consists of three elements: a representative firm in the ETS sector, a set of administrative rules for the EU ETS, and an exogenous technological development.

The representative firm represents all firms in the ETS sector that demand allowances. Firms such as renewable energy producers, which do not demand allowances, but produce ETS sector goods, are not explicitly modeled. These firms are instead implicitly modeled through a change in the demand for goods produced by the representative firm.

The representative firm maximizes the net present value of its profit stream. Greenhouse gas emissions are an unavoidable by-product of the firm's production process. Allowances are allocated to the firm in accordance with a predefined administrative system. It is assumed that allowances are a scarce resource, and the cap-and-trade system therefore constrains the production of the firm. Ultimately, the firm's problem is to consume its allowances optimally over time. As the representative firm represents a large number of small firms, it does not take the effects of its own actions on the allowance surplus and the MSR into account, when solving its optimization problem.[14]

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[12]An additional reason to focus on stationary installations is that aviation operates under a separate emissions cap. Specifically, aviation operators can use so-called European Union Aviation Allowances to comply with the EU ETS system, while this type of allowances cannot be used by stationary installations. However, aviation operators can also use allowances from the stationary sector (European Commission, 2018). The net allowance demand from aviation amounted to 23 m. allowances in 2016 (European Environment Agency, 2017b). This remains a tiny fraction of overall allowance demand. Verified emissions from stationary sources amounted to more than 1,750 m. tonnes of $CO_2$ in 2016 (European Environment Agency, 2017b).

[13]The increase in the linear reduction rate was suggested by the European Commission, the European Parliament and the Ministry Council (European Parliament 2018). Hence, the increase was probably expected by the market participants.

[14] In other studies, the representative firm minimizes costs, while the firm maximizes profits in the present study. The two approaches are more or less identical, as they both require implicit or explicit assumptions on future demand for goods produced by the firm as well as emission abatement costs.

Finally, there is an exogenous technological development that increases the productivity of both the representative firm and its renewable energy competitors. In the following, the technological level refers to the relative technological level between the two types of producers. As renewable energy technologies are relatively less mature, these are expected to be developed relatively faster. The technological development is, therefore, assumed to reduce the demand for goods produced by the fossil fuel consuming representative firm. This development will, however, slow down over time as the renewable technologies become relatively more mature.

### 3.2 The representative firm

The profit of the representative firm depends on both its fossil fuel use and the technological level. An unavoidable by-product from the use of fossil fuels is $CO_2$ emissions. Thus pollution emission becomes an indirect production factor. The firm's profit in period $t$ is given by the function $f(e_t, A_t)$, where $e_t$ is the firm's $CO_2$ emissions and $A_t$ is the technological level. A reduction in $A_t$ represents a relative increase in the technological level of renewable production technologies. Fuel switching is captured by the functional form of the profit function and the development in the technological level. The profit function increases in $e_t$ for $e_t < \bar{e}_t < \infty$, after which it decreases in $e_t$. This assumption ensures that in absence of a cap-and-trade system, emissions remain finite. Specifically, the emissions of the firm equal $\bar{e}_t$ in the absence of the cap-and-trade system. This prediction becomes useful when calibrating the model.

The EU allocates $y_t$ allowances to the representative firm at the beginning of period $t$. These allowances are either newly issued allowances or allowances freed from the MSR. At the beginning of period $t$, the representative firm holds $B_t$ allowances. This stock of allowances is also the allowance surplus ultimo period $t-1$. The stock of allowances held by the representative firm in primo period $t+1$ equals the firm's stock primo period $t$ plus allowances allocated to the firm in period $t$ minus the firm's emissions during period $t$: $B_{t+1} = B_t + y_t - e_t$.

The representative firm's problem is given by:

$$\max_{e_t \geq 0} \sum_{t=1}^{T} \left(\frac{1}{1+r}\right)^{t-1} f(e_t, A_t) \quad st. \quad B_{t+1} = B_t + y_t - e_t, \quad B_t \geq 0,$$
$$given \quad B_1 > 0, \quad \{y_t\}_{t=1}^{T} \quad and \quad \{A_t\}_{t=1}^{T},$$

where $r > 0$ is the firm's investment return requirement (or discount rate).

There is no explicit allowance price in the model. Instead, the allowance price is implicitly given by the shadow price of emissions. The shadow price represents the value to the firm of one unit of emission and thereby an additional allowance.

The allowance price is calculated from the first-order conditions:

$$p_t = f_e'(e_t, A_t) \quad and \quad p_{t+1} = (1 + r)p_t,$$

where $p_t$ is the shadow price of emissions and thereby the allowance price, and $f_e'(e_t, A_t)$ is the first derivative of $f(e_t, A_t)$ with respect to $e_t$. The first condition simply states that in optimum the cost of purchasing one additional allowance must equal the marginal profit from emission. The second condition states that if the firm saves an allowance for later use, the value of that allowance must increase with the investment return requirement. If the return is higher, the firm would save more allowances, and if the return is less, the firm should use more allowances in period $t$. The condition implies that the allowance price increases by a rate equal to the firm's investment return requirement as long as there is an allowance surplus. Note that the second first-order condition only applies for interior solutions. In the corner solution, where no allowances are banked, $e_t = B_t + y_t$, only the first condition applies.

### 3.3 The administrative rules

The administrative rules of the EU ETS determine how the allowances are allocated to the representative firm and the MSR. Newly issued allowances are denoted $z_t$. The path of newly issued allowances is computed from the rules described above. However, the allowances allocated to the representative firm might deviate from $z_t$ due to the MSR.

The MSR is described by two difference equations. Before stating these difference equations, the following dummy variables are defined:

$$D_t^{U1} = I(B_t > 0.833 \ \wedge z_t \geq 0.12 \cdot B_t),$$
$$D_t^{U2} = I(B_t > 0.833 \ \wedge z_t < 0.12 \cdot B_t),$$
$$D_t^{L1} = I(B_t < 0.400 \ \wedge M_t \geq 0.1),$$
$$D_t^{L2} = I(B_t < 0.400 \ \wedge M_t < 0.1),$$

where the function $I(\cdot)$ equals one if the statement inside the parenthesis is true, and $M_t$ is the stock of allowances in the MSR primo period $t$.

In the pre-reform scenario, the allowance allocation to the representative firm is given by:

$$y_{t+1} = z_{t+1} + 0.1 \cdot D_t^{L1} + M_t \cdot D_t^{L2} - 0.12 \cdot B_t \cdot D_t^{U1} - z_{t+1} \cdot D_t^{U2}.$$

The MSR becomes active in 2019, where the stock of allowances in the MSR is given by:

$$M_{t+1} = M_t - 0.1 \cdot D_t^{L1} - M_t \cdot D_t^{L2} + 0.12 \cdot B_t \cdot D_t^{U1} + z_{t+1} \cdot D_t^{U2}.$$

In the reform scenario, the system becomes slightly more complicated. First, the dummies $D_t^{U1}$ and $D_t^{U2}$ are modified such that the intake rate is doubled until 2023. Next, the reform places a cap over the stock of allowances in the MSR from 2023. The cap equals the auctioning volume of the previous years. The new reform ensures that 57 pct. of the newly issued allowances are auctioned from 2021 (EU 2018a, Article 1). The MSR cap in period $t+1$, $\bar{z}_{t+1}$, equals $0.57$ multiplied by the amount of newly issued allowances in period $t$, adding or subtracting allowances allocated to the MSR in period $t$, as these are taken from the auctioning volume, cf. EU (2015). The MSR cap is given by the following equation from 2024:[15]

$$\bar{z}_{t+1} = \max\{0;\ 0.57 \cdot z_t + 0.1 \cdot D_{t-1}^{L1} + M_{t-1} \cdot D_{t-1}^{L2} - 0.12 \cdot B_{t-1} \cdot D_{t-1}^{U1} - z_t \cdot D_{t-1}^{U2}\}.$$

From 2023, the MSR evolves according to:

$$M_{t+1} = \min\{M_t - 0.1 \cdot D_t^{L1} - M_t \cdot D_t^{L2} + 0.12 \cdot B_t \cdot D_t^{U1} + z_{t+1} \cdot D_t^{U2}; \bar{z}_{t+1}\}.$$

### 3.4 The technological development

The technological development has two counteracting effects on the representative firm's profit. First, it reduces the demand for goods produced by the firm, as competing renewable energy firms become more productive and thus steal a larger share of the market. Second, the technological development also increases the productivity of the representative firm which, all other things equal, increases the firm's profits.

In the following, it is assumed that the former effect dominates due to a catching-up effect. Hence $A_t$ is reduced over time. The catching-up effect reflects that renewable energy technologies are relatively less advanced from the offset. Over time they are catching-up to the fossil fuel based technologies, but the speed of this catch up is reduced over time.

[15] The intake rate is 24 pct. in 2022, and thus, the equation must be modified accordingly for 2023.

To catch these dynamics, the technological level evolves according to the two difference equations:

$$A_{t+1} = A_t(1 - g_t), \quad A_1 > 0,$$

$$g_{t+1} = \frac{g_t}{1+\kappa}, \qquad g_1 > 0, \qquad \kappa \geq 0,$$

where $g_t$ is the technological growth rate, and the parameter $\kappa$ reflects how fast the catching-up effect is depleted. If $\kappa = 0$ then $A_t$ is reduced at a constant rate, $g_1$, over time, and $A_t$ approaches zero as time approaches infinity. If $\kappa > 0$ then $g_t$ is reduced by about $100 \cdot \kappa$ pct. per year for small values of $\kappa$. In this case, $A_t$ converges to a number strictly above zero.

### 3.5 Specifying the profit function

The profit function is specified such that the inverse demand function is relatively more elastic for low allowance prices. The feature captures the heterogeneous cost for firms covered by the EU ETS for reducing greenhouse gas emissions.

The profit function is given by:

$$f(e_t, A_t) = A_t[\gamma(e_t + \varphi)^\alpha - \delta e_t - \omega] - p^f e_t, \;\; 0 < \alpha < 1, \qquad \gamma, \varphi, \delta, \omega, p^f > 0,$$

where $\gamma A_t(e_t + \varphi)^\alpha$ is the value of output, $\delta A_t e_t$ is all variable costs except fossil fuel inputs, $A_t\omega$ is a quasi-fixed cost,[16] $p^f$ is the constant fossil fuel price, and $p^f e_t$ is the cost of fossil fuel input. It is assumed that $\omega = \gamma\varphi^\alpha$. Hence the profit is zero if the firm chooses not to emit any greenhouse gasses. The assumption $\varphi > 0$ ensures that the marginal product of the fossil fuel input does not approach infinity for $e_t$ approaching zero. As a result, the firm might cease production within its planning horizon.

In the absence of the EU ETS, the firm's problem is reduced to a static optimization problem for each period. The firm chooses the emission level:

$$\bar{e}_t = \left(\frac{\alpha\gamma A_t}{A_t\delta + p^f}\right)^{\frac{1}{1-\alpha}} - \varphi. \qquad (1)$$

[16] A cost the firm must pay as long as production occurs, but which is independent of the production scale. A typical example is lights in a factory.

Note that $\bar{e}_t$ is reduced over time, as $A_t$ exhibits negative growth. This prediction is consistent with the steady decline in ETS sector emissions before the introduction of the EU ETS in 2005 (see European Environment Agency, 2017a), and it is used to calibrate the model in section 3.7.

The inverse demand function is derived from the first-order conditions:

$$p_t = A_t[\alpha\gamma(e_t + \varphi)^{\alpha-1} - \delta] - p^f. \quad (2)$$

### 3.6 Solving the model

The model can be solved numerically using value function iteration, when the profit function is specified (see Adda and Cooper 2003). The only complication is that the representative firm perceives the allowance allocations as exogenous. Meanwhile the firm's actions affect the allowance allocations through the allowance surplus and the MSR.

To solve the model, the following algorithm inspired by Adda and Cooper (2003, p. 242-244) is employed:

1. Solve the firm's problem given a guess for the allowance allocation. The guess is denoted $\{\bar{y}_t\}_{t=1}^T$, and the initial guess equals the path for newly issued allowances, $\{z_t\}_{t=1}^T$.
2. The policy function for $\{e_t\}_{t=1}^T$ from the first step is used to simulate the model. The resulting allowance allocation path is denoted $\{\hat{y}_t\}_{t=1}^T$.
3. If the guess, $\{\bar{y}_t\}_{t=1}^T$, is sufficiently close to the resulting path, $\{\hat{y}_t\}_{t=1}^T$, the process stops. Specifically, the process stops if:

   $$tol > \sum_{t=1}^{T} (\bar{y}_t - \hat{y}_t)^2,$$

   where $tol$ is a tolerance parameter.
4. If the process has not stopped in step 3, the guess is updated by setting $\{\bar{y}_t\}_{t=1}^T$ equal to $\{\hat{y}_t\}_{t=1}^T$, and the process is repeated from step 1.

Experimenting with different profit functions and parameter values suggests that the algorithm ensures that $tol$ converges quickly to zero.

### 3.7 Calibration

To obtain plausible forecasts, the model is calibrated to match historical observations for the EU ETS. First, a number of initial conditions and parameter values are determined. The remaining parameters are thereafter calibrated using a two-step procedure.

The allowance surplus primo 2017, $B_1$, is set to 1693 m. allowances based on EU (2017). The stock of allowances in the MSR primo 2017, $M_1$, is set to 1550 m.[17] The price of fossil fuels is set to 40.5 Euros per tonne of $CO_2$.[18] The representative firm's investment return requirement, $r$, is set to 5 pct.[19] The technological level in 1990 is set to one, and $\kappa$ is set to 1 pct. Finally, $\varphi$ is set to one.[20]

The model is calibrated to match the following three targets:[21]

1. ETS sector emissions in 1990: 2.7 billion tonnes of $CO_2$.
2. ETS sector emissions in 2004: 2.4 billion tonnes of $CO_2$.
3. Market situation in 2017: the allowance price is 5.8 Euros if the EU ETS sector emissions are 1.7 billion tonnes of $CO_2$.

The first and second calibration targets ensure that the model can match the historical emission trend before the ETS was in introduced in 2005. The model gives clear predictions on this account according to equation (1). The third target ensures that the model can match the current market situation. In particular, the target ensures that the current market situation is a point on the inverse demand function for 2017.

The first step in the two-step calibration procedure is to compute $\alpha, \delta$, and $\gamma$ from equations (1) and (2) using the three calibration targets. As the three parameter values can be determined using three equations, the three parameter values are uniquely determined. To compute the three values, it is necessary to compute the technological levels in 1990 and 2004. This is done by assuming a technological growth rate from 1990 to 1991

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[17] This number is computed from the expected number of unallocated allowances in 2020, and the 900 m. allowances back-loaded into the MSR according to EU (2015) and the European Commission (2017a). According to European Commission (2015b), market participants expected that between 550 and 700 m. allowances were transferred to the MSR in 2020. There are currently more than 300 m. unallocated allowances in the New Entrants Reserve (European Commission, 2018) and about 300 m. unallocated allowances due to closures and changes in production capacity (European Commission, 2017c). Based on European Commission (2015a, 2017c, 2018), the latter has historically increased faster than the former. Thus, it seems fair to assume that more than 600 m. unallocated allowances are placed in the MSR by 2020. In this paper, we assume that 650 m. unallocated allowances are placed in the MSR, but the exact number is not important for the results presented below.

[18] The fossil fuel price is based on the average projected coal price from the Danish Energy Agency (2017) over the period 2015 to 2040.

[19] Perino and Willner (2017) use a return requirement of 10 pct. p.a., while Fell (2016) uses a return requirement of 3 pct. p.a. In general, risky returns should yield a return of about 7 pct. p.a., cf. Jordà et al. (2017). However, firms can also hold allowances to hedge against future price movements. This reduces the required return below that of a standard risky asset. Neuhoff et al. (2012) find EU ETS coved firms hedging their risk on allowance price movements require a return of 5 pct. p.a. The return requirement is discussed further in section 5, and it is shown that the main results can also be obtained using a lower or higher return requirement.

[20] As shown in section 5, similar results can be obtained with different values of $\kappa$ and $\varphi$. The model is not very sensitive to these parameters due to the remaining part of the calibration procedure.

[21] Emissions are based on European Environment Agency (2017a) and the allowance price is computed based on EEX (2018).

which is denoted $\bar{g}$. The entire path $\{A_t\}_{t=1}^{T}$ is then computed based on $\bar{g}$ and $\kappa$ as well as the difference equations for $A_t$ and $g_t$.

In the second step, the growth rate $\bar{g}$ is determined such that the model matches the allowance price and the ETS emissions in 2017. As the market situation in 2017 is located on the inverse demand function for 2017 due to the first step in the calibration procedure, the target can be matched by minimizing the squared error between the computed and actual allowance price in 2017. To compute the 2017 allowance price, it is necessary to run the entire simulation. After each simulation, step one is repeated to ensure that the model matches the three calibration targets from the first step.

After the calibration procedure, the model matches all calibration targets with very small numerical deviations. Table 1 shows assumed and calibrated parameter values.

*Table 1. Assumed and calibrated parameter values*

| | | | |
|---|---|---|---|
| $\alpha$ | 0.186 | $\omega^{b)}$ | 710 |
| $\gamma$ | 710 | $\bar{g}$ | 0.006 |
| $\varphi^{a)}$ | 1.000 | $\kappa^{a)}$ | 0.010 |
| $\delta$ | 5 | $r^{a)}$ | 0.050 |

a) Exogenous.

b) Computed from $\alpha$, $\varphi$ og $\gamma$, as stated in section 3.5.

Note: The presented numbers are rounded. Numbers above one are rounded to thousandths, and numbers below one are rounded to whole numbers.

Source: Own calculations based on the model presented above.

# 4 Analysis

The model simulations presented in this section should be interpreted with caution. The idea is to present a plausible development to illustrate likely consequences of the reform. In particular, we want to investigate whether the new mechanism introduced by the MSR cap is relevant over the coming years. Yet, the exact numbers presented below are associated with a large degree of uncertainty.

This section is divided into two parts. In the first part, two baseline scenarios of the model are presented. We distinguish between a pre-reform baseline and a post-reform baseline. The post-reform baseline illustrates the effects on the pre-reform baseline scenario of the recent reform. We show how the reform affects the allowance price and the aggregate variables in the EU ETS (emissions, allowance surplus and allowance stock in the MSR) over time. The second part focuses on the effects of national policies before and after the recent reform.

### 4.1 Baseline effects of the reform

To reiterate, the three key changes of the reform are: (1) increased yearly allowance reduction rate; (2) increased MSR uptake rate until 2023; and (3) a cap on allowances in the MSR. We include the first change in the pre-reform baseline.[22] The difference to the post-reform baseline therefore shows the consequences of the two other policy changes.

As shown in subfigure (a), $CO_2$ emissions decrease systematically in the pre-reform baseline scenario until 2060. Thereafter the yearly $CO_2$ emissions are exactly 100 m. tonnes until 2097, where emissions again start dropping.

The systematic reduction in emissions until 2060 is caused by the scarcity of emission allowances, the discount rate, and the technological development. The scarcity of allowances implies that the firms need to priorities when to use their allowances. Due to discounting and the relatively faster technological development of competing renewable technologies, the firms choose to emit more at the beginning of the period despite the concavity of the profit function.

To understand the emission pattern after 2060, consider the allowance surplus shown in subfigure (b) and the stock of allowances held in the MSR shown in subfigure (c). The allowance surplus is above 833 m. until 2036. As a result, a large amount of allowances are placed in the MSR at the beginning of the period. The allowance surplus remains above 400 m. until 2048. Thus from 2048 the MSR starts supplying the firms with 100 m. additional allowances. As the allowance surplus drops to zero in 2060, emissions are solely driven by allowances leaving the MSR. And since the MSR contains more than 5 billion allowances primo 2048, it takes more than 50 years to exhaust it.

The development in the allowance surplus reflects the representative firm's desire to smooth out its consumption of allowances. The emission path is therefore smooth while the allowance surplus path is lumpy.

As discussed above, the allowance price increases by 5 pct. per year as long as there is an allowance surplus. When there is no longer a surplus of allowances, the allowance price starts to drop until 2098 as shown in subfigure (d). This drop is caused by the relatively faster technological development of renewable energy competitors, as the con-

[22] We include the increased reduction rate, as this change was suggested by all three EU institutions (EU-Commission, Council and European Parliament) and thus anticipated by the market participants.

sumed amount of allowances is constant. In 2098 there are no more allowances leaving the MSR and the consumed amount of allowances drop which increases the marginal profits associated with allowance use. This results in a price increase from 2098 to 2100.

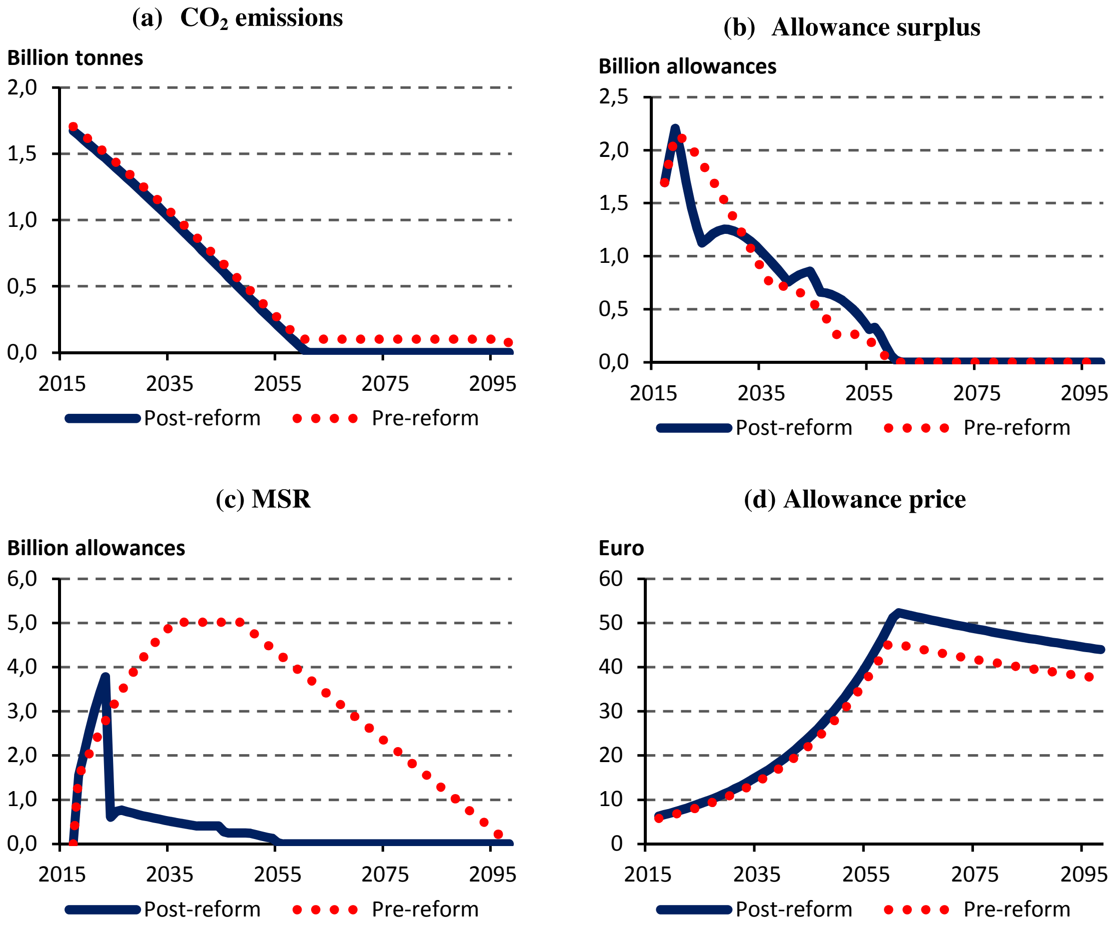
In the post-reform baseline scenario, emissions drop at all moments in time compared with the pre-reform scenario. The reduction in emissions is basically a result of the additional allowance scarcity introduced by the reform. In the short run, the reform introduces additional scarcity by increasing the allowance intake rate into the MSR. And in the long-run, the reform introduces additional scarcity through allowance cancellations in the MSR.

The emission difference between the two scenarios is especially large after 2060, where emissions drop to zero in the post-reform scenario, while emissions are constant at 100 m. tonnes in the pre-reform scenario. This difference is caused by the fact that the MSR does not contain any allowances in the post-reform scenario after 2055. This is a consequence of the MSR cap which results in massive allowance cancellations. Most significantly, the MSR cap results in more than 3 billion allowance cancellations in 2023 (the year where the MSR cap is introduced). Yet allowances are also cancelled due to the MSR cap at later dates, as the MSR cap is systematically lowered as discussed in section 2.2. In the end, around 6 billion allowances are cancelled by the MSR cap in the post-reform scenario.

Interestingly, the reform does not reduce the allowance surplus in the short run. This is because the reform has two counteracting effects on the allowance surplus. On the one hand, the reform increases the MSR intake rate until 2023 which reduces the surplus. On the other hand, the reform increases allowance scarcity in both the short and long run. As the firms covered by the EU ETS do not take the effects of their own actions on the allowance surplus into account when maximizing profits, this additional scarcity results in additional allowance saving. This effect increases the allowance surplus. The total effect is small but positive, and the reform therefore only has a small short-run impact on the allowance surplus.

The reform increases the allowance price at all points in time. This is again a consequence of the additional allowance scarcity introduced by the reform. As fewer allowances are consumed at any point in time, the marginal profit – and thereby the allowance price – is higher at any point in time.

*Figure 3.* The allowance price and aggregate variables, 2017-2100




Source: Own calculations based on the model presented above.

The general trend is that the allowance surplus decreases over time. This means that after some cut-off date, the allowance surplus is so small that no further allowances are placed in the MSR. As discussed previously, this cut-off date is important, because national policies have the same effect in the pre-reform and the post-reform baseline scenarios after this date. In the post-reform baseline, the surplus is below 833 m. allowances in 2039 and up until 2042, but a lumpy surplus path means that the surplus once again exceeds 833 m. allowances in 2043 and 2044. From 2045 and onwards, the surplus does not exceed 833 m. allowances. Thus, the new mechanism is relevant until the mid-2040s. Yet the two later years of allowance intake are not that important. To ease comparison with simulations considered below, we define the cut-off date as the first year where the surplus is below 833 m. allowances.

Table 2 summarizes the results of the reform on aggregate emissions. Aggregate emissions are reduced relatively more in the long run than in the short and medium run. Again, this difference is caused by the cap over allowances in the MSR. In the short and medium run, the allowance scarcity is not changed much by the MSR cap, as the allowances cancelled in the MSR were not available to market participants anyway. As a consequence, the firms in the EU ETS do not change their behavior much compared with the pre-reform baseline scenario. However, in the long run, the MSR cap introduces additional scarcity. After 2060, emissions are entirely covered by allowances leaving the MSR in the pre-reform scenario. In the post-reform scenario, these allowances are cancelled by the MSR cap, and thus there is no emission after 2060. Aggregate emissions are thus reduced by 100 m. tonnes of $CO_2$ per year after 2060 due to the reform.

*Table 2. The effect of the reform on aggregate $CO_2$ emissions*

| 2030 | 2050 | 2100 |
|---|---|---|
| | ---------- percent ---------- | |
| -2,6 | -4,3 | -13,8 |

Note: The effect is computed as a deviation from baseline.
Source: Own calculations based on the model presented above.

Other studies in the literature also find that the MSR cap leads to substantial allowance cancellations; although the 6 billion cancelled allowances found in the present study lies at the high end of the scale. Sandbag (2017) finds that about 3 billion allowances are cancelled in 2023 due to the MSR cap. Meanwhile, in an illustrative numerical simulation using a model with forward-looking agents, the National Institute of Economic Research (2018) finds that the MSR cap leads to the cancellation of 2.9 billion allowances before 2080. And the Danish Council on Climate Change (2017) finds that long-run cumulative emissions drop by more than 5 billion tonnes.

At the other end of the scale, Perino and Willner (2017) find that 1.7 billion allowances are cancelled over the entire period due to the MSR cap. The difference between our results and those obtained by Perino and Willner (2017) are mainly caused by two factors. Firstly, this paper assumes a relatively faster technological development for renewable energy technologies compared to fossil fuel based technologies. This mechanism explains the systematic emission reductions for the ETS sector before the introduction of the EU ETS in 2005. Perino and Willner (2017) do not allow for this mechanism, resulting in a slower emission reduction rate over the coming years. In addition, Perino and Willner (2017) assume that firms' in the EU ETS requires a 10 pct. return for holding allowances, while this paper only assumes a return requirement of 5 pct. Thus, the allowance price increases faster in the study by Perino and Willner (2017). This increases the incentive to pollute at the beginning of the investigated period, which means that fewer allowances are placed in the MSR. The choice of discounting rate is discussed in further detail in section 5.

## 4.2 Effects of national policies

This section presents the consequences of national policies before and after the reform. Following the discussion in section 2, two types of national policies are considered. Both policies are small in scale compared to the EU ETS, and they are designed such that they do not change the cut-off date.[23]

The first policy reduces the demand for goods produced by the representative firm. The policy thereby reduces the demand for allowances, and thus, it is referred to as the demand policy. Examples of demand policies include subsidies to renewable energy, a national carbon tax, and energy efficiency requirements. The second policy is national allowance cancellations. EU member states auction off allowances, but could choose to instead cancel some amount of these in order to curb long-run emissions.[24]

The allowance cancellation policy is straightforward to model: it corresponds to a decrease in the supply of allowances over some period. The cancellations considered here are uniformly distributed over a predefined time period.

The demand policy is modeled by introducing the parameter $\phi_t$ into the profit function such that:

$$f(e_t, A_t) = A_t[\phi_t \gamma (e_t + \varphi)^\alpha - \delta e_t - \omega] - p^f e_t.$$

The parameter $\phi_t$ is below one while the policy is active and equals one otherwise. If, for instance, an EU member state builds a wind farm, the demand for goods produced by the representative firm is reduced as long as the wind farm operates. Hence $\phi_t$ is below one, while the wind farm operates, and $\phi_t$ equals one at all other moments in time.

The considered demand policy reduces $CO_2$ emissions by 10 m. tonnes over the period where the policy is active, given the baseline allowance price path. Hence for the time periods were the demand policy is active, $\phi_t$ is computed from the demand function of the firm holding the allowance price path fixed at the baseline level. The specific $\phi_t$

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[23] If a national policy were to change the cut-off date, the impact of such a policy would potentially be much larger than suggested here. However, as the exact time profile of the allowance surplus is extremely difficult to predict, it is unlikely that national policymakers intentionally are able to affect the cut-off date. To ensure comparability between shocks and to report only policy relevant estimates, the shocks considered here are intentionally designed such that the cut-off date remains unchanged.

[24] Private persons, organizations, and companies can also cancel allowances using Article 12(4) of Directive 2003/87/EC (EU, 2003). Private allowance cancellations would have the same effects as the national cancellation policies investigated in this paper.

value is chosen such that $CO_2$ emissions are reduced by 10 m. tonnes over the active policy period. When simulating the actual effect of the policy, the short-run net effect on emissions is less than 10 m. tonnes, as the policy reduces the allowance price over the affected period.[25]

The time profiles of the national policies turn out to be important. To illustrate this, we model policies with a ten-year or a 25-year time horizon. Table 3 shows the effects of the two types of national policies in the case where the national policies last for 10 years, starting in 2021.

In the pre-reform scenario, the demand policy postpones $CO_2$ emissions by increasing the stock of allowances in the MSR. The additional allowances absorbed by the MSR are not available to the representative firm until the MSR is depleted in the 2090s. However, the reform has no effect on long-run aggregate emissions. Note that the short-run effect on aggregate emissions is less than 10 m. tonnes. The reason is that the allowance price is reduced by the policy, resulting in a small increase in allowance use.

Post-reform, the demand policy not only postpones $CO_2$ emissions. It also decreases long-run aggregate emissions, as allowances placed in the MSR due to the policy are cancelled. Thus the reform introduces a new mechanism, which has the potential to increase the long-run effectiveness of demand policies.

The cancellation policy has a small impact on emissions in the short run both before and after the reform. This is because the policy has two counteracting effects on the available quantity of allowances in the short run. The cancellations directly reduce the supply of allowances, but they also reduce the allowance surplus and thereby the intake of allowances in the MSR. The former effect dominates, but the net effect is relatively small.

Pre-reform, the cancellation policy reduces long-run aggregate emissions one-to-one: the cancellation of one allowance results in a reduction of one tonne of $CO_2$. Post-reform, the cancellation policy has a less than one-to-one effect on long-run aggregate emissions. When allowances are cancelled in the 2020s, the representative firm reduces its saving of allowances. Thus the allowance surplus is reduced and fewer allowances end up in the MSR. This reduces the amount of allowances cancelled in the MSR. Hence the total effect of the cancellation policy is less than one-to-one.

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[25] We note that the shock sizes considered here are different in size from those considered in Beck and Kruse-Andersen (2018). This change affects the absolute effect sizes but does not affect the share of the shock that is transmitted into emissions reductions.

*Table 3. Reduction in accumulated $CO_2$ emissions from 2017 caused by a national policy that directly reduces the accumulated $CO_2$ emissions by 10 m. tonnes over the period 2021-2030*

| | **2030** | **2050** | **2100** |
|---|---|---|---|
| | --------- m. tonnes of $CO_2$ --------- | | |
| **Pre-reform scenario** | | | |
| Demand policy | 9.1 | 7.4 | 0.0 |
| Cancellation policy | 0.9 | 2.6 | 10.0 |
| | | | |
| **Post-reform scenario** | | | |
| Demand policy | 9.5 | 8.5 | 8.0 |
| Cancellation policy | 0.5 | 1.5 | 2.0 |

Source: Own calculations based on the model presented above.

The figures in table 3 indicate that demand policies are relatively more effective in terms of reducing long-run emissions both pre-reform and post-reform. This is, however, not a particularly robust conclusion. Firstly, table 3 shows the effects on emissions of two policies with the same absolute effect on direct demand and allowance supply, but not the costs of implementing these two policies. Secondly, the direct effect of the demand policy is net of carbon leakage outside the allowance system. If an additional wind farm is built in Denmark, this might reduce the incentive to expand wind power capacity in Germany. Given that the construction of the Danish wind farm leads to a smaller expansion of the German wind power capacity, the net effect of the Danish wind farm on the EU ETS allowance demand is reduced. The direct effect of the demand policy in table 3 corresponds to the effect of the Danish wind farm after subtracting the reduced German supply of wind energy.

Finally, the time profiles of the policies are important for the computed effects. This is because the new mechanism introduced by the MSR cap stops, when the MSR stops its allowance intake. Any demand reductions that take place after the cut-off date are not affected by the reform. Therefore, demand-affecting policies that partly reduce demand after the cut-off date become relatively less effective in terms of reducing long-run emissions, compared to policies whose direct effect is concentrated before the cut-off date. In contrast, allowance cancellation policies become more effective if parts of their effect take place after the cut-off date. This is because the counteracting effect on the cancellation policy from reduced allowance intake into the MSR is eliminated after this date.

These effects are illustrated in table 4, where the direct effects of the national policies are assumed to work over a 25-year period starting from 2021. The cut-off date for the MSR is 2038, which means that the demand policy now works on both sides of the cut-off date. This reduces the effectiveness of the demand policy substantially in the post-reform scenario. In contrast, the cancellation policy becomes more effective in the post-reform scenario, as there is no MSR intake to erode the long-run effects of the policy after the cut-off date.

*Table 4. Reduction in accumulated $CO_2$ emissions from 2017 caused by a national policy that directly reduces the accumulated $CO_2$ emissions by 10 m. tonnes over the period 2021-2045*

| | **2030** | **2050** | **2100** |
|---|---|---|---|
| | --------- m. tonnes of $CO_2$ --------- | | |
| **Pre-reform scenario** | | | |
| Demand policy | 2.5 | 4.0 | 0.0 |
| Cancellation policy | 2.1 | 6.4 | 10.0 |
| | | | |
| **Post-reform scenario** | | | |
| Demand policy | 3.0 | 5.4 | 3.9 |
| Cancellation policy | 1.7 | 5.0 | 6.8 |

Source: Own calculations based on the model presented above.

As illustrated above, the timing and time profiles of national policies become important for their long-run impact on $CO_2$ emissions after the reform. This substantially increases the complexity of cost-benefit analyses of national policies that aim to reduce $CO_2$ emissions. For example, in order to compute the long-run impact of a demand policy, it is necessary to forecast the developments of the allowance surplus, stock of allowances in the MSR, and the MSR cap. It is, of course, also necessary to decide on a time profile of the national policies, but this seems like a minor issue in comparison.

The cancellation policies discussed above are simple and not particularly designed to reduce long-run aggregate emissions. A smarter cancellation policy would be to buy the allowances and store them until the MSR stops absorbing allowances. In that way, the allowances purchased for cancellation would count as a part of the allowance surplus and increase the amount of allowances cancelled in the MSR. Of course, this type of policy introduces commitment issues, as a future government might sell a stock of allowances originally purchased for cancellation purposes.

Our computations show that the delayed cancellation policy described above can have a more than one-to-one effect on aggregate emissions in the long-run. Specifically, we find that purchasing 1 m. allowances every year over the period 2021-30 (10 m. allowances in total) and storing them until the MSR is empty will result in a reduction in long-run aggregate emissions of 15.2 m. tonnes of $CO_2$. The additional impact of this type of policy comes from a demand reaction in the allowance market. As fewer allowances are available to firms in the EU ETS due to the cancellation policy, they will save more allowances. This increases the intake of allowances in the MSR which further reduces the available amount of allowances.

It should also be noted that allowance cancellations conducted in accordance with the flexibility mechanism for the non-ETS sector have similar effects. Certain EU member states are allowed to cancel a pre-defined amount of EU ETS allowances to reduce their emission reduction obligations. If these member states do so, these cancelled allowances still count on the supply side – but not on the demand side – when the allowance surplus is determined (EU 2018b). Thus this type of allowance cancellations will have a more than one-to-one impact on long-run aggregate emission in the EU ETS. For instance, Denmark can cancel up to 8 m. allowances uniformly distributed over the period 2021-30.[26] Our calculations suggest that this policy will reduce long-run aggregate emissions in the EU ETS by around 12 m. tonnes of $CO_2$.

## 5 Robustness analysis

In this section, the robustness of the simulations from section 4 is analyzed. The effects of national policies depend critically on the cut-off date for the MSR, i.e. the date where the MSR stops absorbing allowances. This date is associated with a large degree of uncertainty, as EU ETS emissions depend on various factors including business cycles and expectations about future technological developments. This section investigates how sensitive the effects of national policies are to two critical and hard-to-predict parameters, namely the discounting rate and the rate of relative technological progress in renewables compared to fossil fuels.

The focus of the robustness analysis is the MSR cut-off date. Before the cut-off date, the MSR cap changes the main principles of the EU ETS as described in section 2. But after the cut-off date, the system returns to the basic cap-and-trade principles. Thus, the cut-off date shows when the system switches between the two regimes, and it, therefore, constitute the main finding of the numerical analysis.

Table 5 shows how the cut-off date changes when the model is calibrated and simulated under different assumptions. In the main model specification, the cut-off date is 2039. If the catching-up parameter $\kappa$ is reduced to zero, implying that the catching-up effect for renewable technologies is not diminished over time, the cut-off date is increased to 2040. In a more pessimistic scenario, the catching-up parameter is increased to 1.75

[26] The 8 m. allowances are computed based on figures from EU (2018b) and Danish Energy Agency (2018). The number corresponds to 2 pct. of the Danish emissions in the non-ETS sector in 2005.

pct., implying that the catching-up effect is reduced notably faster. This pessimistic assumption moves the cut-off date to 2038. The exercise shows that the exact value of the catching-up parameter is not crucial for the obtained results. This result is partly caused by the calibration procedure: if the catching-up effect is weak, the relative growth rate of the green sector must be higher today in order to explain current allowance prices and emissions.

Another debatable parameter choice is the value of the return requirement or discount rate. Perino and Willner (2017), as well as Silbye and Sørensen (2017), use a discounting rate of 10 pct. p.a. This parameter choice can be motivated by a study by Neuhoff et al. (2012), who conducted a survey on allowance market participants between November 2011 and January 2012. They find that market participants require a return of 10-15 pct. p.a. for holding EU ETS allowances after their hedging requirement has been fulfilled. However, this period exhibited a large degree of uncertainty about the future of the EU ETS. In fact, at the time several media questioned whether the EU ETS would survive within a foreseeable future.[27] Investors would have required a high return on allowance investments, when Neuhoff et al. (2012) conducted their survey to counteract the political risk associated with their investments. It seems reasonable to assume that the situation is different today, given the latest reform of the EU ETS which signals a will to preserve and strengthen the EU ETS. Still, one might argue that the discount rate should be above the 5 pct. used in the main specification since the long-run returns on risky assets have been around 7 pct. p.a. historically, cf. Jordà et al. (2017). On the other hand, firms in the EU ETS might require a return below the long-run returns on risky assets, as they are also hedging their risk on the allowance price by holding allowances. In fact, Neuhoff et al. (2012) find firms that hedge their risk require a return of 5 pct. p.a., consistent with our man specification. Still, the robustness analysis investigates the cases $r = 0.04$ and $r = 0.07$ to test the robustness of the results obtained above.

The model reacts strongly to changes in the representative firm’s discount rate (or return requirement). This is not surprising given the exponential discounting of profits. The value in 2017 of earning 1 euro in 2040 is reduced from 0.33 to 0.21 euro if the discount rate is increased from 5 to 7 pct. Even small changes to the discount rate will therefore substantially change the incentive to use allowances at different points in time.

[27] Salant (2016) documents that several media were questioning the legitimacy of the EU ETS in the beginning of 2013. The Economist (2013), for instance, wrote a critical article on the EU ETS in April 2013 with the title “ETS, RIP”.

*Table 5. The sensitivity of the MSR cut-off date*

| Change compared with main specification | MSR cut-off date |
|---|---|
| None | 2039 |
| Optimistic technological development[a)] | 2040 |
| Pessimistic technological development[b)] | 2038 |
| High return requirement[c)] | 2056 |
| Low return requirement[d)] | 2036 |
| High value of $\varphi$[e)] | 2039 |
| Low value of $\varphi$[f)] | 2045 |

a) $\kappa = 0$.
b) $\kappa = 0.0175$.
c) $r = 0.07$ and $\varphi = 0.05$.
d) $r = 0.04$ and $\varphi = 2$.
e) $\varphi = 1.1$.
f) $\varphi = 0.2$.
Note: The MSR cut-off date is defined as the first year after 2019, where the MSR stops absorbing allowances.
Source: Own calculations based on the model presented above.

If only the discount rate is changed, the calibration procedure leads to violations of the parameter restrictions for $\alpha, \delta,$ or $\gamma$. To avoid this problem, the parameter $\varphi$ is also changed. Intuitively, if the discount rate is increased, the incentive to emit today increases. The calibration procedure needs to reduce the incentive to emit pollution today such that the model can match the market situation (emissions and allowance price) in 2017. The mechanical procedure described in section 3.7 will partly do this by reducing the technological growth rate. However, a reduced technological growth rate also implies a less concave profit function, as the model is also forced to match the declining emission trend from 1990 to 2004. This basically means an increase in $\alpha$. Even small changes in a discount rate can change the value of a given emission path substantially. Thus even for small changes in $r$, the procedure forces $\alpha$ outside of the predefined parameter space. To counteract this mechanism, we reduce $\varphi$ when $r$ is increased and increase $\varphi$ when $r$ is decreased. Experimenting with different values of $\varphi$ indicate, that the robustness results for the return requirement are not sensitive to the exact change in $\varphi$, as long as it ensures that the parameter restrictions are not violated.

Table 5 reports cut-off dates for simulations based on 4 and 7 pct. discount rates. The cut-off date is moved further out in time as the discount rate is increased to 7 pct. At first, this might seem counter intuitive, as a higher discount rate increases the incentive to expedite emissions. However, as the model is calibrated to match the current market situation, a higher discount rate results in a more inelastic demand for allowances and a slower technological growth rate. The opposite holds when the discount rate is lowered. The figures from table 5 show that the model is sensitive to changes in the discount rate, but also that the cut-off date remains well after 2030 in both cases.

Finally, table 5 reports cut-off dates for simulations based on lower and higher $\varphi$ values compared with the main specification. The parameter $\varphi$ ensures that the marginal productivity of emissions does not approach infinity as emissions approach zero. Thus $\varphi$ ensures that the representative firm uses all allowances before 2125. In this robustness check, we choose values of $\varphi$ such that the parameter $\alpha$ comes close to its limit values after running the calibration procedure. It is thus not possible to choose $\varphi$ values much higher or lower than the ones used here. Specifically, $\varphi$ is set to 0.2 and 1.1 resulting in $\alpha$ values of about 0.9 and 0.1 respectively. The results reported in table 5 indicate, that the obtained results are not sensitive to changes in $\varphi$.

## 6 Concluding remarks

The latest reform of the EU ETS introduces a new mechanism that fundamentally changes the main principles of the system. Before the reform, the EU ETS placed a politically determined cap over emissions from the ETS sector of the EU. After the reform, the emissions cap depends on the various aggregate EU ETS variables including the allowance surplus. Hence, the reform basically turns an exogenously determined cap into an endogenous one. As a consequence, the EU policymakers have lost the direct control over long-run emissions.

The model simulations conducted above indicate that the reform increases the allowance price and reduces emissions in both the short and long run. However, the reform does not seem to have a notable effect on the allowance surplus, which may be of a substantial size in the foreseeable future.

The simulations also indicate that the reform has larger effects on long-run aggregate emissions, while the reform has only a small impact on emissions over the next couple of decades. This is because even without the reform, the MSR would ensure that a large amount of allowances would remain unavailable to the market for many years. Thus, the substantial amount of allowances cancelled in the MSR due to the new cap on allowances in the MSR would not have been available to firms for decades anyway. As a consequence, the cap over allowances in the MSR has a small effect on firm behavior in the short and medium run.

However, we show that the reform has significant implications for national policies. As allowances placed in the MSR can be cancelled after the reform, national policies can affect the effective emissions cap. For instance, building a wind farm can after the reform reduce long-run emissions. This is because a wind farm reduces the demand for allowances in the short and medium run. This increases the allowance surplus and thereby the MSR allowance intake. If the cap over allowances in the MSR is binding, this leads to allowance cancellations. In contrast, cancelling allowances will reduce the allowance surplus and thereby allowance cancellations in the MSR. Thus, the reform implies that allowance cancellation policies become less effective.

As the cut-off date – the year where the MSR stops absorbing allowances – remains highly uncertain, so do the effect on emissions of national policies such as wind farms or allowance cancellations. A main weakness of the reform is precisely this: it substantially increases the complexity of the EU ETS as well as the uncertainty associated with effects of national policies. The increased complexity makes it difficult, if not impossible, for member states to construct cost-effective national climate policies. To address this issue, it could be useful to remove the cap over allowances in the MSR in a future revision of the EU ETS. This could be done without affecting expected long-run aggregate emissions if the linear reduction factor for newly issued allowances is adjusted appropriately.

Even though the reform introduces uncertainty regarding long-run effect sizes of national policies, the simulations conducted in this paper provide useful insights on what long-run effective national policies look like. If an EU member state wants to reduce aggregate emissions within the EU ETS using demand-driven policies, this should be done as soon as possible to ensure that the policy increases the MSR intake. On the other hand, if the EU member state wants to use allowance cancellations, it is more effective to postpone these cancellations until the MSR stops absorbing allowances.

Finally, it is worth emphasizing an additional weakness of the reform: it makes electrification less attractive seen from an environmental perspective. This is because electrification increases the demand for allowances. Electrification of industries that today use fossil fuels and that are not covered by the EU ETS – mainly transport and private heating installations – increase the demand for electricity. Since the overwhelming majority of plants that use fossil fuels to generate electricity are covered by the EU ETS, electrification increases the demand for allowances. This reduces the allowance surplus and thereby the allowance intake into the MSR. This leads to increased emissions in the short run, but it also increases long-run emissions, as fewer allowances are cancelled within the MSR.

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