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TOWARDS A MORE EFFICIENT EUROPEAN CARBON MARKET

by

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Abstract: We discuss the prospects for the European Emissions Trading System (ETS) after the 2018 reform of the system. For this purpose we set up a simple model of the ETS with forward-looking market behaviour. The model is calibrated to current market data and incorporates the future rules for the allocation of emission allowances, including the Market Stability Reserve taking effect in 2019. The model simulations indicate that the current allowance surplus may not disappear until some time in the 2050s if no further tightening of allowance supply is undertaken. They also show that the new mechanism for annulment of surplus allowances held in the Market Stability Reserve fundamentally changes the properties of the ETS by endogenizing the long-run supply of emission allowances. Due to this mechanism annulment of allowances at the EU member state level may be largely ineffective whereas subsidies to renewable energy can permanently reduce EU-wide CO_2 emissions. We present a simple model of the political economy of the ETS which may explain the basic features of the recent ETS reform. We also suggest that the next ETS reform should include a floor and a ceiling for the price of emission allowances to replace the complex Market Stability Reserve.

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by Frederik Silbye[1] and Peter Birch Sørensen[2]

1. Introduction: The European Emissions Trading system versus national climate policies

Economists have long pointed out that the costs of cutting global greenhouse gas emissions may be reduced by allowing international trade in emission rights. The Emissions Trading System (ETS) in the European Union is so far the most important attempt to reap the gains from trade in CO_2 emission allowances, accounting for over three quarters of international carbon trading. The ETS covers the energy sector and energy-intensive industrial emitters, representing about 45 percent of total greenhouse gas emissions in the EU (see European Commission (2017)).

Despite the existence of the ETS, member states of the European Union offer extensive government support for renewable energy, including various investment subsidies as well as feed-in tariffs and feed-in premiums for renewables-based electricity production. Many economists - including Böhringer et al. (2008), Eichner and Pethig (2009), Böhringer et al. (2009a, 2009b), Boeters and Koornneef (2011) and Heindl et al. (2015) to name but a few – have been highly critical of the overlapping regulation implied by the combination of national subsidies to renewables and the EU-wide cap-and-trade system for the ETS sector. The critics argue that national subsidies do not benefit the climate since the total emissions from the ETS sector are capped and that they increase the cost of meeting EU climate policy targets by preventing the cross-country equalization of marginal abatement cost that the free trade in emission allowances would otherwise bring about.

On the other hand, many observers have argued that the large surplus of ETS emission allowances keeps the allowance price far below the level needed to spur a quick transition to renewable energy and implies that member state subsidies to renewables within the ETS sector will in fact reduce total emissions in the short and medium term and may help to pave the way for a reduction in total allowance supply (see, e.g., Sandbag (2016a) and the Danish Council on Climate Change (2017)).

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Against this background the present paper seeks to answer four questions: 1) Has the ETS fulfilled its mission so far? 2) What are the prospects for the European carbon market after the 2018 reform of the ETS? 3) Are national policies aimed at reducing emissions from the ETS sector ineffective? 4) How can the future performance of the ETS be improved?

Our analysis has three main implications: First, despite the 2018 ETS reform aimed at reducing the surplus of emission allowances and driving up the allowance price, the allowance surplus is likely to persist for several decades in the absence of further reform. Second, because the 2018 reform endogenizes the total supply of emission allowances, national policy measures that reduce the demand for emission allowances can reduce total European emissions permanently and not just temporarily. Third, the welfare cost of cutting total emissions can be reduced by introducing a minimum and a maximum price of ETS emission allowances.

The present paper extends the analysis in the paper by Silbye and Sørensen (2017) which was written before the recent agreement on reform of the ETS. Like us, Perino and Willner (2017), Beck and Kruse-Andersen (2018), Carlén et al. (2018) and the National Institute of Economic Research (2018) evaluate the effects of the reform using a simple partial equilibrium simulation model of the ETS. We go beyond these studies by analyzing the implications of assigning different social values to emissions cuts occurring at different points in time and by offering estimates of the cost efficiency of different national climate policies intended to reduce total emissions from the ETS sector. Section 4 explains in more detail how our analysis and results deviate from those in other recent studies of ETS reform.

Our proposal for further reform of the ETS builds on an extensive literature on the design of cap-and-trade systems going back to Roberts and Spence (1976). We review this literature in section 7 and add to it by showing how our efficiency-improving reform proposal may be consistent with the political economy of ETS design.

The paper is organized as follows: Section 2 sketches the history of the ETS and offers a brief evaluation of its performance so far. Section 3 sets up a simple partial equilibrium model of the emissions trading system, and section 4 uses the model to evaluate the implications of the 2018 ETS reform for the future evolution of the allowance supply, actual emissions and the allowance price. In section 5 we use the model to estimate the cost-effectiveness of two alternative national measures to reduce emissions from the ETS sector: subsidies to renewable energy versus annulment (or purchase) of ETS allowances by the domestic government. Section 6 reflects on the political economy governing the design of the ETS and section 7 proposes a fundamental reform of the system which could be robust against political economy forces. Our main conclusions are summarized in section 8.

2. A brief history of the European Union Emissions Trading System[3]

The mechanics of the ETS

The ETS covers about 45 percent of CO_2 emissions in the EU[4]. The system applies to CO_2 emissions and equivalent amounts of nitrous oxide and perfluorocarbons from installations in energy-intensive industrial sectors[5]. By April 30 of each year registered firms in the ETS sector must surrender emission allowances corresponding to their emissions in the previous calendar year. Allowances can be freely traded across the EU, and a significant share of allowance trades is handled by banks and financial institutions using allowances as financial assets.

Phase I of the ETS was a pilot stage covering the period from 2005 until the end of 2007. Emission allowances in this phase were distributed freely and could not be "banked" for use in subsequent phases. Phase II coincided with the compliance period 2008-2012 under the Kyoto Protocol. Since the beginning of Phase II, allowances can be banked for use in later phases. The system is currently in Phase III covering the period 2013-2020. From the start of Phase III a significant and growing share of allowances is being auctioned rather than allocated free of charge.

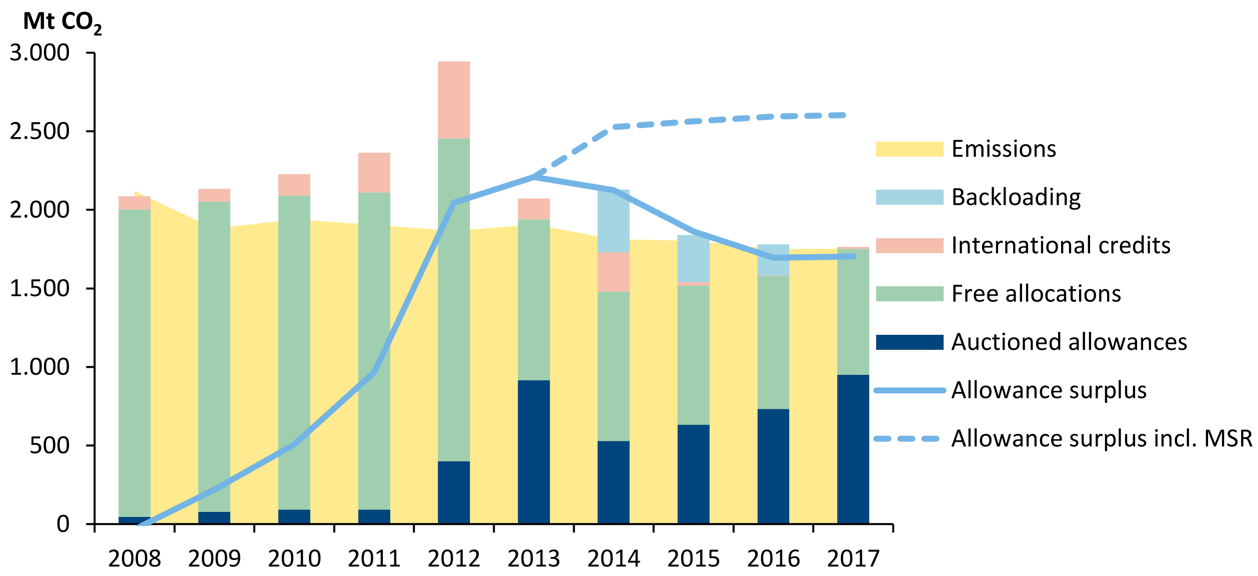
The emissions cap versus actual emissions

Figure 1 shows the aggregate emissions cap for the first three phases of the ETS along with the actual verified emissions and the cumulative surplus of unused allowances over the period 2005-2017. In addition to the allowances issued by the EU, firms in the ETS sector were allowed to use a total of 1,418 million so-called offset units from the Kyoto Protocol flexible mechanisms during

[3] This section draws on Gronwald and Hintermann (2015), Ellerman et al. (2016), and the Danish Council on Climate Change (2017) who offer more detailed accounts of the history of the ETS.
[4] Norway, Iceland and Liechtenstein have linked their national permit systems to the ETS, so the system involves a total of 31 countries.
[5] Since 2012 emissions from aviation have been included as well, but this sector has a separate emissions cap.

Phase II[6]. This has contributed significantly to the cumulative allowance surplus illustrated in Figure 1. Another major factor behind the surplus was the fall in energy demand caused by the Great Recession in 2008-2009 and the subsequent European sovereign debt crisis. National subsidies to renewable energy have likewise contributed to falling demand for emission allowances. The cumulative allowance surplus fell slightly in 2014 and 2015 as some allowances were withheld from the market through an ad hoc measure labelled as "backloading". The current allowance surplus roughly corresponds to one year of emissions.

Figure 1. Allocations, emissions and allowance surplus in the EU ETS.



Note: "Backloading" implied that 400 Mt and 300 Mt of allowances were held back from the market in 2014 and 2015, respectively. The backloaded allowances will be placed in the coming Market Stability Reserve (MSR) from 2019. They are included in the allowances surplus shown by the green graph in the figure.

Source: European Environment Agency, *EU Emissions Trading System data from EUTL*, 2015 *http://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-scheme-10.*

In the current Phase III the total amount of allowances issued under the ETS is reduced linearly at an annual rate of 1.74 percent of the average emissions cap in Phase II. In Phase IV, which will cover the period 2021-2030, the annual linear reduction of the cap will be 2.2 percent. In addition,

[6] These offsets are certified emission reductions under the Clean Development Mechanism and emission reduction units from Joint Implementation in Annex B countries.

the European Council and the European Parliament agreed in the spring of 2018 to establish a so-called Market Stability Reserve (MSR) from 2019 to gradually absorb a part of the allowance surplus.[7] Section 3 describes the detailed mechanics of the MSR which will significantly change the dynamics of the ETS.

Evolution of the price of allowances

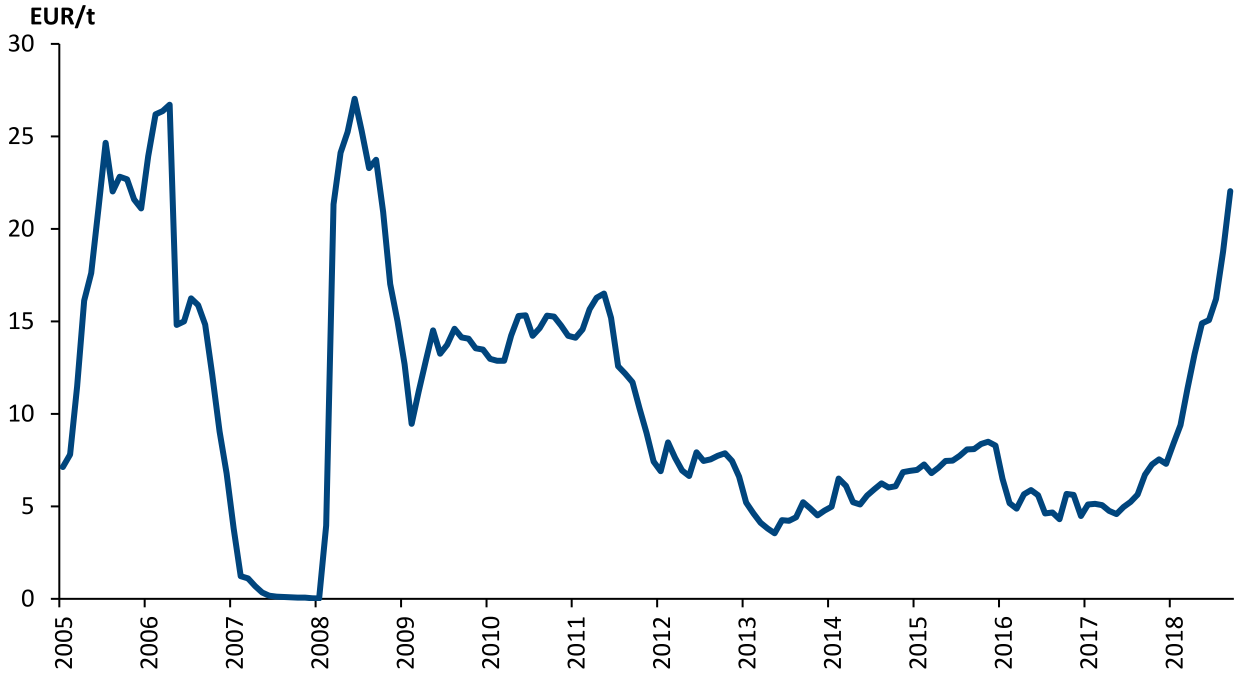
Figure 2 illustrates how the spot price of ETS allowances has evolved. The allowance price has been quite volatile. Towards the end of Phase I the price collapsed to zero as it became clear that the non-bankable allowances issued during this phase would exceed total accumulated emissions. During the first half year of Phase II the allowance price reached its previous peak of around 30 euros per ton emitted, but then the Great Recession quickly drove the price down to around 10-15 euros. As the European sovereign debt crisis deepened in 2011 and 2012, the price was pushed further down to around 5-6 euros.

After rising a bit during 2015, the allowance price came back to the 5-6 euro level in 2016 and hovered around that level throughout the first half of 2017. However, beginning in late 2017 and continuing during 2018, the price rose sharply and reached a level of around 21-22 euros at the time of writing (October 2018).

In an empirical study based on data for the ETS for the period from January 2008 to October 2013, Koch et al. (2014) found that only about 10 percent of the variations in the allowance price could be explained by changes in fundamentals such as expected future economic activity, subsidies to renewables, and additions to the allowance supply from the Kyoto Protocol flexible mechanisms, with the two former explanatory factors being more important than the third one. The authors suggest that changes in the allowance price may have been driven mainly by shifts in market confidence in the willingness of policy makers to sustain the ETS. We shall return to this possibility below when we discuss the potential reasons for the 2018 price surge.

[7] The decision to establish the MSR from 2019 was actually made already in 2014, but the recent agreement between the Council and the Parliament includes an important tightening of the rules for the MSR. See section 3 for details.

Figure 2. The spot price of ETS allowances (euros per ton, monthly average)



Source: EEX, European Emission Allowance Auction (EUA) | Global Environmental Exchange, European Energy Exchange AG, *http://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction#!/2017/01/13* [16.01.2017].

Has the ETS fulfilled its mission so far?

Critics of the ETS would answer “No!”. They point out that the average level of the allowance price has so far been much lower than expected when the ETS was introduced, so the cap-and-trade system has not provided a sufficient incentive to replace fossil fuels by carbon-free sources of energy. The insufficient incentive is further weakened by the fact that the allowance price has been highly volatile, creating great uncertainty about the profitability of development of and investment in green energy technologies. Against that background, critics of the ETS see national taxes on fossil fuel use within the ETS sector and national subsidies to renewable energy in the sector as a reasonable response to the fact that the ETS in itself has not been able to drive the transition to green energy at the pace needed. The critics argue that such national policy measures will in fact reduce total European emissions since the ETS cap on total emissions in non-binding due to the large allowance surplus.

On the other hand, defenders of the system argue that the ETS works in the basic sense that actual emissions do not exceed the emissions cap reflecting the political level of ambition regarding emissions reductions. According to the defenders the substantial amount of trade in emission allowances indicates that the ETS also fulfills its purpose of reallocating abatement efforts towards emitters with the lowest marginal abatement costs, thus helping to reduce the total costs of emissions reductions. The defenders point out that the existence of an allowance surplus does not necessarily indicate that the ETS is inefficient. On the contrary, by saving allowances for future use when the emissions cap is expected to be tighter, firms are able to smooth their abatement costs over time, thus reducing the present value of costs. Finally, defenders of the ETS argue that the large allowance surplus and the resulting low allowance price is due in large part to the national subsidies to renewables which prevent a cross-country equalization of marginal abatement costs and will not succeed in cutting total emissions in the long run when the emissions cap becomes binding.

In the next section we will set up a model of the ETS that will enable us to throw further light on these issues.

3. A simple partial equilibrium model of the ETS[8]

To analyze the effects of the 2018 ETS reform and the impact of alternative national climate policies we now set up a model of the allowance market which accounts for the rules governing the supply of emission allowances. The model determines time paths for the evolution of the allowance price and CO_2 emissions from the ETS sector, given the time path for the annual issue of new allowances and the impact on allowance supply of the new Market Stability Reserve taking effect from 2019.

[8] The model presented in this section is identical to the one presented in Silbye and Sørensen (2017) except that here we explicitly lay out its microfoundations. After having finished the development of the model, we became aware of the papers by Perino and Willner (2016, 2017) who use a very similar model, but with a different calibration leading to different conclusions. We discuss the relationship of our work to theirs in the final part of section 4.

The demand for emission allowances

The demand for emission allowances stems from a representative ETS firm. As part of its maximization of the present value of the net cash flows paid out to its owners, the firm wishes to minimize the present value of its expenses on emission allowances and abatement of its CO_2 emissions. At the beginning of year one, this present value (PV) given by

$$PV = \sum_{t=1}^{h} (1+r)^{-(t-1)} \left(p_t X_t + TAC_t \right), \qquad (1)$$

where p is the real allowance price, X is the firm's acquisition of emission allowances during the period,[9] TAC is its total abatement cost, r is the real discount rate, t is the time period, and h is the firm's planning horizon. The total abatement cost is assumed to increase more than proportionally with the volume of emissions abated, so the marginal abatement cost is positive and increasing. Assuming a quadratic abatement cost function for simulation purposes, we have

$$TAC_t = \frac{1}{2b} \left(\bar{E}_t - E_t \right)^2, \qquad b > 0, \qquad (2)$$

where E is the actual emission of CO_2, and $\bar{E}$ is the emission in the absence of abatement effort. The amount of emission allowances held by the firm in excess of its current emissions is denoted by S. This allowance surplus evolves as

$$S_t = S_{t-1} + X_t - E_t, \qquad S_t \geq 0, \qquad S_0 > 0 \text{ given}, \qquad (3)$$

where S_t measures the allowance surplus at the end of period t. The constraint in (3) that the allowance surplus can be positive but cannot be negative reflects the features of the ETS that banking of allowances for future use is permitted whereas borrowing of future allowances to cover current emissions is not. The firm chooses X_t and E_t so as to minimize the present value of its costs given by (1) subject to the constraints (2) and (3), taking the current and rationally expected future level of the allowance price as given. As shown in Appendix A, the solution to this non-linear programming problem implies that

[9] While the majority of allowances are auctioned, some emission allowances are allocated for free to manufacturing sectors deemed to be exposed to significant risk of carbon leakage, but in this case the allowance price represents an opportunity cost of holding allowances, so equation (1) is valid even for these firms.

$$E_t = \bar{E}_t - bp_t, \qquad E_t \geq 0, \tag{4}$$

$$p_{t+1} = (1+r)\, p_t \quad \text{for} \quad S_t > 0, \tag{5}$$

$$p_{t+1} \leq (1+r)\, p_t \quad \text{for} \quad S_t = 0. \tag{6}$$

Eq. (4) reflects that cost-minimizing firms will abate emissions up to the point where the marginal abatement cost $b^{-1}\left(\bar{E}_t - E_t\right)$ implied by the abatement cost function (2) is equal to the price of emission allowances. Eq. (5) is a "Hotelling Rule" reflecting that saving allowances for the future is worthwhile only if the expected return to such saving matches the firm's required return *r*. The expected return to investment in allowances is the expected increase in their price. If the allowance surplus is zero ($S_t = 0$), the current allowance price must be so high that the expected return to saving allowances for the future falls short of (or at least does not exceed) the firm's required return, as stated in (6).

The supply of emission allowances

From 2019 the supply of ETS allowances will be regulated by the new Market Stability Reserve (MSR) mentioned in section 2. Taking the firm modelled above as representative of the entire ETS sector, the annual CO_2 emission is *E*, and each year a quantity Q of new emission allowances is allocated to the market either free of charge or by auction. In addition, a quantity M^{OUT} of allowances may be released from the *MSR* in the year considered, or a quantity M^{IN} of allowances may be transferred to the reserve. If the allowance surplus at the end of year zero is S_0, the cumulative surplus at the end of year t will therefore be

$$S_t = S_0 + \sum_{i=1}^{t}\left(Q_i - E_i - M_i^{IN} + M_i^{OUT}\right). \tag{7}$$

According to the recent agreement on ETS reform, a fraction of the allowance surplus must be transferred to the MSR if the surplus exceeds 833 million tons of CO_2. The transfer is based on the surplus recorded (almost) two years earlier,[10] and the fraction to be transferred is 24 percent until

[10] More precisely, if the allowance surplus at the end of year *t* exceeds 833 Mt, the transfer of a fraction of the excess amount to the MSR takes place from the start of September of year *t+1* until the end of August in year *t+2*, so there is

the end of 2023 and 12 percent in the subsequent years. With end-of-year dating of stocks, we thus have

$$M_t^{IN} = \begin{cases} 0.24 \cdot S_{t-2} \text{ for } t \leq 2023 \text{ and } 0.12 \cdot S_{t-2} \text{ for } t \geq 2024 & \text{if } S_{t-2} > 833 \\ 0 \quad \text{if } S_{t-2} \leq 833 \end{cases} \tag{8}$$

The rules for the MSR also stipulate that allowances amounting to 100 million tons of CO_2 (or the entire remaining reserve if this is smaller than 100 million tons) must be released from the reserve whenever the allowance surplus recorded (almost) two years earlier falls short of 400 million tons, whereas no release can take place at a surplus above this level. If the stock of allowances held in the *MSR* at the end of year $t-1$ is M_{t-1}, we therefore have

$$M_t^{OUT} = \begin{cases} \min\{100, M_{t-1}\} & \text{if } S_{t-2} < 400 \\ 0 & \text{if } S_{t-2} \geq 400 \end{cases} \tag{9}$$

Furthermore, from 2023 there will be a cap (denoted by *C*) on the amount of allowances that can be held in the MSR. Allowances above the cap will be permanently annulled. The cap will equal the amount of allowances that was auctioned during the previous year. This amount is equal to 57 percent of newly issued allowances in the previous year plus any release of allowances from the reserve in the previous year (since releases must be auctioned) and minus any transfers of allowances to the reserve in the previous year (since these must be taken from the flow of new allowances that is auctioned). Hence the cap evolves as

$$\begin{aligned} &C_t = 0 \quad \text{for} \quad t < 2023 \\ &C_t = 0.57 \cdot Q_{t-1} + M_{t-1}^{OUT} - M_{t-1}^{IN} \quad \text{for} \quad t \geq 2023 \end{aligned} \tag{10}$$

The cumulative reserve in the MSR at the end of year t can now be written as

$$M_t = \min\left\{M_{t-1} + M_t^{IN} - M_t^{OUT}, C_t\right\}, \tag{11}$$

where the first term in the curly bracket applies whenever the cap on the MSR is non-binding.

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an almost two-year long time lag before the full transfer is completed. For ease of exposition, eq. (8) assumes a full two-year lag, but our simulation model correctly accounts for the actual time lag.

The equilibrium allowance price

Whenever there is a positive allowance surplus, the allowance price will be positive only if the market expects that the surplus will vanish in some future period T ($S_T = 0$) so that allowances become scarce. In Appendix A we use the model above to show that if there is an allowance surplus in period 1 which will vanish in period $T > 1$, the equilibrium allowance price in period 1 will be

$$p_1 = \frac{r\left(\bar{E}_T^a - S_0 - Q_T^a + M_T^a\right)}{b\left[\left(1+r\right)^T - 1\right]},$$

$$\bar{E}_T^a \equiv \sum_{i=1}^{T} \bar{E}_i, \qquad Q_T^a \equiv \sum_{i=1}^{T} Q_i, \qquad M_T^a \equiv \sum_{i=1}^{T}\left(M_i^{IN} - M_i^{OUT}\right). \tag{12}$$

The variable $\bar{E}_T^a$ measures the total amount of CO_2 that would have been emitted from period 1 through period *T* if the ETS had not existed (i.e., if the allowance price had been zero), Q_T^a is the total number of new allowances issued from period 1 through period *T*, and M_T^a is the total net amount of allowances transferred to the MSR over that time span.

The result in (12) suggests why the allowance price rose significantly from 2017 to 2018: The ETS reform that was finally agreed upon in March 2018 involves a substantial initial transfer of allowances to the MSR and introduces the permanent annulment of allowances above the cap specified in eq. (10), so forward-looking market agents will expect an increase in our variable M_T^a in eq. (12). The demonstration of a political will to tighten up the ETS may also have created expectations that future changes to the system will lead to further cuts in emission allowances as part of the recurrent tightening of international climate policy prescribed by the 2015 Paris Agreement. In any case, the reduction in the allowance supply implied by the 2018 ETS reform has presumably created a market expectation that the allowance surplus will vanish sooner than previously believed, implying a fall in our variable *T*.

These changes in M_T^a and T tend to raise the current equilibrium allowance price according to (12), and since ideas for tightening of the MSR rules were discussed in public well before the final agreement on the ETS reform, the reform was anticipated to some extent by the market. This helps to explain why the price started to go up already in late 2017. But eq. (12) suggests a further possible explanation for the recent rise in the allowance price: The final reform agreement following several years of hard bargaining resolved some of the uncertainty regarding the future of the ETS and probably increased market confidence in the system. It seems likely that holding allowances for future use or sale is now seen as a less risky investment. In that case the reform has lowered the risk premium included in the required rate of return *r* in our eq. (12), thereby helping to drive up the allowance price (since (12) implies that p_1 is decreasing in *r* for any $T > 1$). We return to this issue in section 4.

Measuring the effects of national climate policies

In section 5 we will use our model of the ETS to analyze the effects on EU-wide emissions of two types of national climate policy: An annulment of emission allowances undertaken by an EU member state, or a policy measure such as a national carbon tax or a national subsidy to renewable energy that reduces the demand for ETS emission allowances in a member state.

A member state government can implement the annulment policy either by abstaining from auctioning some of the emission allowances that have been allocated to it or by purchasing allowances in the market and withdrawing them from circulation. In a situation with an allowance surplus, such a policy undertaken in period 1 will work like a reduction of Q_1 in the definition of our variable Q_T^a in (12). Since the changes in emissions occurring in different future years do not necessarily have the same present social value per unit, we assume that a unit change in emissions occurring one year from now has a present social value of $1/(1+\rho)$, where the discount rate ρ may or may not exceed zero (we discuss the determinants of ρ below). Let CER_H^Q denote the discounted value of the cumulative emissions reduction from year 1 through year H induced by a unit reduction in the supply of emissions allowances in year 1. Formally,

$$CER_H^Q \equiv \sum_{t=1}^{H} \frac{dE_t / dQ_1}{(1+\rho)^{t-1}}, \qquad \rho \geq 0. \tag{13}$$

We will refer to the expression in (13) as the *Coefficient of Emission Reduction* (*CER*). We see that the *CER* depends on the policy horizon H as well as on the social discount rate applied to future emissions. If 1) the supply of allowances (including uptake in and release from the MSR) were fully exogenous, 2) the discount rate were zero, and 3) the accumulated emissions exceed the accumulated issues of allowances in finite time, then the *CER* defined in (13) would always be 1, i.e., annulment of an allowance would always reduce the accumulated emissions by a similar amount even in the presence of a temporary allowance surplus. However, from 2019 the allowance supply will in fact become endogenous due to the complex mechanics of the MSR described above, and the cap on the MSR raises the possibility that annulment of allowances by individual member states may be (partly) offset by fewer annulments of allowances held in the MSR. In that case the *CER* defined in (13) will be less than one even in the absence of discounting.[11]

A member state policy such as a subsidy to renewable energy that reduces the demand for emission allowances in period 1 by one unit can be modelled as a unit reduction in the exogenous variable $\bar{E}_1$ in the definition of our variable $\bar{E}_T^a$ in (12). At any given allowance price, such a policy will thus reduce the demand for allowances by one unit, and according to (12) it will have the same effect on the allowance price as a unit increase in the newly issued allowances Q_1. From the definition of the *CER* stated in (13) it therefore follows that the total *reduction* of the discounted cumulative emissions from year 1 through year H induced by a policy that reduces the demand for allowances by one unit will be

$$CER_H^R = 1 - CER_H^Q. \tag{14}$$

The *R*-superscript on the left-hand side of (14) indicates that we imagine a subsidy to renewable energy, but the formula applies to any other policy that reduces the demand for ETS emission allowances, e.g. a national carbon tax. Equation (14) highlights the tight link between the dynamic effects on emissions of a change in the supply of emission allowances and the dynamic effects of a subsidy to renewables which lowers the demand for allowances.

Our Coefficients of Emission Reduction CER_H^Q and CER_H^R may be used to calculate the cost-effectiveness of alternative national climate policies. Specifically, if SC_t^Q is the social cost in year t of annulling one ton of emission allowance in year 1, and SC_t^R is the social cost in year t of increasing renewable energy production in year 1 by an amount causing a unit fall in our demand

[11] The CER will also be less than one if condition 3) above is violated, i.e., if the allowance surplus never goes away, say, because rapid technical progress in green energy technologies leads to a fast reduction in the demand for allowances, as described in Scenario 2 in Silbye and Sørensen (2017).

shift variable $\bar{E}_t$ (thereby reducing emissions by one ton at the given allowance price), we can compare the cost-effectiveness of these two policies by comparing the ratios

$$\theta_H^Q \equiv \frac{1}{CER_H^Q} \sum_{t=1}^{H} \frac{SC_t^Q}{\left(1+r^s\right)^{t-1}}, \tag{15}$$

$$\theta_H^R \equiv \frac{1}{CER_H^R} \sum_{t=1}^{H} \frac{SC_t^R}{\left(1+r^s\right)^{t-1}} = \frac{1}{1-CER_H^Q} \sum_{t=1}^{H} \frac{SC_t^R}{\left(1+r^s\right)^{t-1}}, \tag{16}$$

where r^s is a social discount rate which may deviate from the discount rate *r* applied by firms in the ETS sector.[12] The ratios θ_H^Q and θ_H^R measure the present value of the social costs of achieving a unit reduction in the present value of emissions over the policy horizon H. When calculating the social cost of climate policy, we must account for the direct costs as well as the welfare effects of the induced changes in energy prices. We adopt the following crude measure of social welfare (*SW*) in year t,

$$SW_t = CS_t + PS_t + p_t Q_t^d - \left(c_t^R - q_t\right) R_t, \tag{17}$$

where CS is the consumer surplus from household energy consumption, PS is the producer surplus from energy consumption in the business sector, Q^d is the quantity of emission allowances which the domestic government is entitled to issue under the rules of the ETS, q is the price of energy, R is the quantity of domestic renewable energy production, and c^R is the cost of producing one unit of renewable energy. We measure R and Q^d in comparable units, so one unit of R generates a one unit drop in our demand shift parameter $\bar{E}_t$, i.e., a unit rise in R causes emissions to fall by one ton at any given allowance price *p*. The magnitude $c^R - q$ is the subsidy required to cover that part of the unit cost of renewable energy which cannot be covered by the

[12] For example, the private discount rate *r* may include a risk premium due to policy uncertainty about the future rules of the ETS.

market price of energy. Hence the magnitude $pQ^d - \left(c^R - q\right)R$ is the net government revenue from climate policy, consisting of the revenue pQ^d from auctioning allowances[13] minus the total subsidy to renewable energy production. We assume that the government controls the quantity R of renewable energy by determining how many units of R to subsidize.

Using (17) plus standard results from the theory of consumer and producer surplus, we show in Appendix B that when the policy horizon H does not extend beyond the year T when the allowance surplus vanishes, the (inverse) cost effectiveness ratios defined in (15) and (16) can be written as

$$\theta_H^Q = \frac{p_1}{CER_H^Q}\left[1 - \varepsilon_1 \sum_{t=1}^{H}\left(\frac{Q_t^d - F_t^d}{\tilde{Q}_1}\right)\left(\frac{1+r}{1+r^s}\right)^{t-1}\right] \quad \text{for } H \le T, \tag{18}$$

$$\theta_H^R = \frac{p_1}{1 - CER_H^Q}\left[\frac{c_1^R - q_1}{p_1} + \varepsilon_1 \sum_{t=1}^{H}\left(\frac{Q_t^d - F_t^d}{\tilde{Q}_1}\right)\left(\frac{1+r}{1+r^s}\right)^{t-1}\right] \quad \text{for } H \le T, \tag{19}$$

$$\varepsilon_1 \equiv -\frac{dp_1}{dQ_1^d}\frac{\tilde{Q}_1}{p_1} > 0, \qquad \tilde{Q}_1 \equiv S_0 + M_0 - M_1 + Q_1,$$

where F_t^d is the domestic demand for emission allowances in year t, $\tilde{Q}_1$ is the total quantity of allowances available to the European market in year 1, and ε_1 is the numerical elasticity of the allowance price with respect to total EU-wide allowance supply (measured in year 1). The terms involving $Q_t^d - F_t^d$ in (18) and (19) capture terms-of-trade effects of national climate policy. For example, when the domestic government drives up the equilibrium allowance price by annulling an emission allowance, this price increase will impose a cost on the domestic economy to the extent that it is a net importer of allowances ($Q_t^d - F_t^d < 0$), and vice versa.

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[13] In practice some emission allowances within the ETS are distributed for free, but the resulting loss of government revenue is matched by a corresponding gain to the firms receiving the allowances, so equation (17) remains valid as a measure of social welfare when Q^d is interpreted as the total number of allowances issued by the domestic government (whether by auction or free of charge).

The formulas (18) and (19) apply in the case where the policy horizon is no longer than the time span before the allowance surplus vanishes. If the policy horizon is longer, the formulas for cost effectiveness become more complicated, but they will still include terms-of-trade terms of the form $\left(Q_t^d - F_t^d\right)/\tilde{Q}_1$ which will only amount to very small numbers for a small EU member state. For a small country with a negligible impact on the allowance price the terms-of-trade effects may therefore be ignored as a first approximation when calculating the cost-effectiveness of national climate policies. In this case where the summation terms on the right-hand sides of (18) and (19) are roughly zero, the formulas apply for any policy horizon, including scenarios where $H > T$.

Choosing a discount rate for future emissions

When evaluating the effect of a policy measure on the future time path of emissions, we must compare the social cost of changes in emissions that occur at different times in the future. If the social discount rate on conventional consumption goods is given by the standard Ramsey formula $r^s = \theta + \varepsilon g$, where r^s is usually measured by the marginal real rate of return on capital, θ is the pure rate of time preference (the utility discount rate), ε is the elasticity of the marginal utility of consumption, and g is the growth rate of per-capita consumption, the discount rate ρ applicable to a physical unit of emissions one period ahead may be found from the formula

$$\frac{1}{1+\rho} = \frac{1+g^d}{1+r^s} = \frac{1+g^d}{1+\theta+\varepsilon g}, \tag{20}$$

where g^d is the rate of increase of the social cost of carbon (*SCC*), defined as the present value of the future damage costs caused by the emission of an extra ton of CO_2. The *SCC* is often assumed to rise roughly in line with the growth rate of total output. Denoting the rate of population growth by n, we then have $g^d \approx g + n$, and with the popular assumption of a logarithmic utility function where $\varepsilon = 1$, eq. (20) would imply that $\rho \approx \theta - n$.[14] According to the 2015 forecast by the United Nations, the global population is expected to grow at an average annual rate of about 0.8 percent over the period to 2050. For any rate of time preference exceeding this number, the approximation

[14] Assuming a logarithmic utility function in a Ramsey set-up, Golosov et al. (2014) derive a damage cost formula which implies that the SCC does in fact rise at the rate of output growth. For a rich discussion of the parameters determining the SCC and its rate of growth, see van den Bijgaart et al. (2016).

$\rho \approx \theta - n$ would thus call for a positive discount rate for future CO_2 emissions. Based on the latest version of his Dynamic Integrated Model of Climate and the Economy (DICE), Nordhaus (2017) estimates our parameter g^d to be roughly 3 percent per annum over the period to 2050, while our variable r^s averages $4\frac{1}{4}$ percent per year in his model simulation. According to (20) these numbers imply that $\rho \approx r - g^d \approx 1\frac{1}{4}$ percent.

Overall, these crude observations suggest that we should apply a modest positive discount rate to future physical emission flows. This is in line with the extensive literature on the so-called Green Paradox of climate policy sparked by the contribution by Sinn (2008) which assumes that postponing emissions is socially desirable (see, e.g., Gerlagh (2011) and van der Ploeg and Withagen (2012)). On the other hand, Stern (2007) and many others have argued that adopting a pure rate of time preference significantly above zero is unethical in the context of climate policy, and Hoel and Sterner (2007) and Sterner and Persson (2008) have shown that if the substitutability between conventional and environmental goods is low and the latter goods become scarcer as a result of climate change, the parameter g^d is not necessarily smaller than r^s even if one assumes a rate of time preference in line with the so-called descriptive approach taken by Nordhaus. It is also widely accepted that, given the uncertainty regarding future rates of return on capital and the future damages from climate change, the discount rate should be declining with time (see Arrow et al. (2014)).

Against this background the quantitative analysis in this paper will consider the implications for climate policy of applying three different annual discount rates to future physical CO_2 emissions: 0%, 1% and 2%. If the Nordhaus estimate of an annual increase in SCC of about 3% is broadly correct, these alternative values of our parameter ρ imply that the (rising) future damage costs of climate change are discounted at annual rates of roughly 3%, 4% and 5%, respectively, since these are the approximate values of r^s implied by (20).

4. The effects of the 2018 reform of the ETS

We will now use a calibrated version of our model of the ETS to evaluate the effects of the 2018 reform on the likely evolution of the future allowance surplus and the future CO_2 emissions from the sector. The main change in the system is the new Market Stability Reserve taking effect from

2019. The introduction of the MSR from that year was agreed upon already in 2015, but without a cap on the total allowances held in the reserve. The 2018 agreement on the rules for Phase IV of the ETS introduced the cap on the MSR described by our eqs. (10) and (11) and raised the rate of transfer of surplus allowances to the MSR from 12 percent to 24 percent in the period from 2019 to 2023.

To highlight the effects of these separate elements of the MSR, we will compare the pre-reform situation without the MSR to two post-reform scenarios: one in which the MSR follows the rules agreed upon in 2015, and one in which the reserve evolves according to the final rules decided in 2018. In all three scenarios we assume that, starting from the beginning of Phase IV in 2021, the issue of new emission allowances is reduced linearly at an annual rate of 2.2 percent of the average emissions cap in Phase II (up from the 1.74 percent annual reduction during Phase III), since this tightening of the system has been planned for a long time. Thus our analysis focuses on the effects of the MSR and assumes that the 2.2 percent annual reduction of new allowance issues will be maintained until the level of new issues hits zero.

Calibrating the model

Our abatement cost function (2) implies that the marginal abatement cost in year *t* is $MAC_t = b^{-1}\left(\bar{E}_t - E_t\right)$. This specification allows for downward shifts in the marginal abatement cost curve over time due to progress in energy efficiency and in the efficiency of green energy technologies. To account for such factors which tend to reduce emissions at any given allowance price, we assume that

$$\bar{E}_{t+1} = \left(1-z\right)\bar{E}_t, \qquad z > 0, \tag{21}$$

where z is a constant.

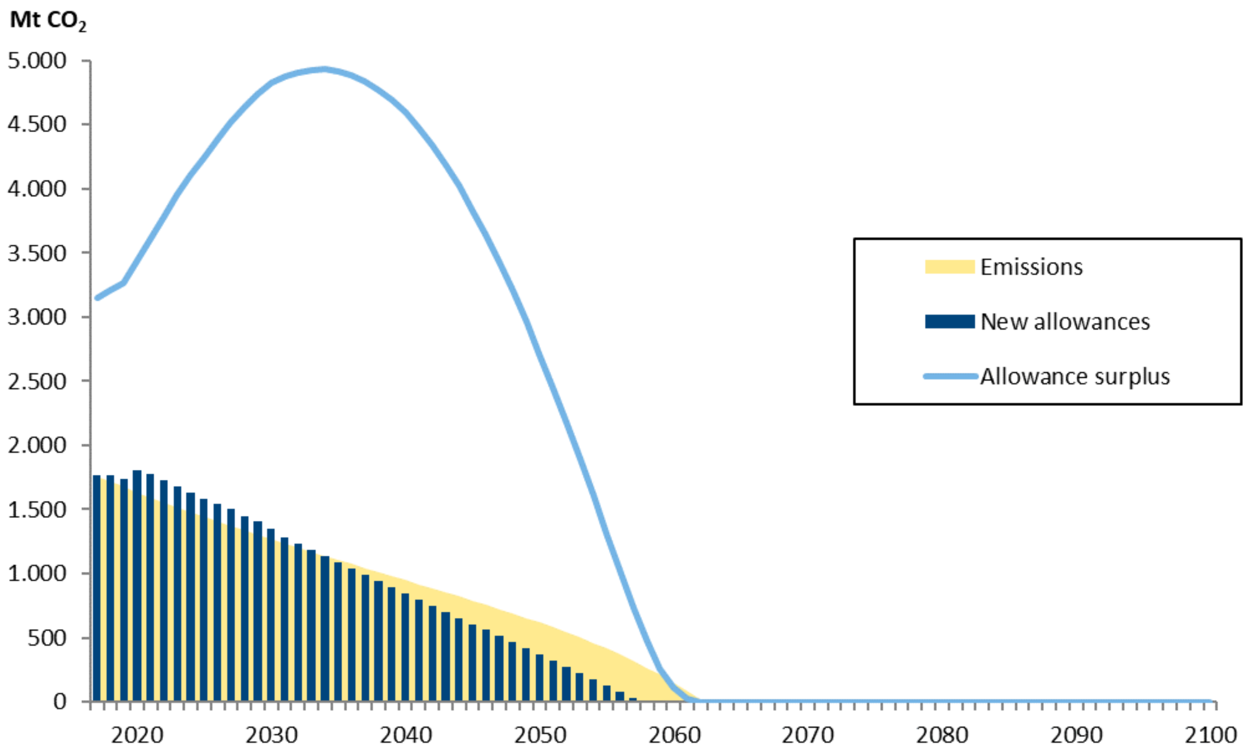
To simulate our model we must choose values of the parameters r, b, and z as well as the initial level of $\bar{E}_t$, denoted by $\bar{E}_0$. When calibrating the model to the market situation in 2017, we set the required expected annual return on allowances (r) equal to 10 percent, corresponding to the assumption made in the simulations by Perino and Willner (2016) and Sandbag (2016b). This is roughly in line with the study by Neuhoff et al. (2012) who found that the marginal investors holding ETS allowances as a speculative investment required expected returns in the order of 10-15 percent. Our price sensitivity parameter b is set equal to 2.2, implying that a rise in the allowance price of one euro causes a drop in emissions amounting to 2.2 million tons of CO_2. Again, this accords with the assumption made in Sandbag (2016b) which is based on the price response of the market to date and studies of marginal abatement cost curves. The parameters z and $\overline{E}_0$ are then chosen so that the model reproduces the 1,754 million tons of CO_2 emissions and the average allowance price of 5.8 euros per ton of CO_2 observed in 2017, assuming that the market in 2017 correctly expected the linear annual reduction of new allowance issues to be raised to 2.2 percent from the start of Phase IV of the ETS and that it expected the MSR rules agreed upon in 2015 to be activated from 2019.[15] With this calibration based on the rules for allowance supply expected to prevail prior to the 2018 reform, the model predicts an average annual fall in actual emissions of 2.57 percent over the period 2017-2030, roughly identical to the average annual reduction of 2.5 percent observed between 2005 and 2017.

Effects of the 2015 and 2018 ETS reforms

Using this calibration we can illustrate the impact of the MSR rules planned in 2015 by comparing figures 3 and 4. Figure 3 shows the evolution of emissions and the allowance surplus from 2017 and onwards predicted by the model in a hypothetical situation without the MSR. We see that, without the MSR, one could have expected a gigantic surplus to accumulate until the mid-2030s. From around 2034 the issue of new allowances would tend to fall short of actual emissions, so the allowance surplus would gradually start to fall, but would not be eliminated until around 2063.

[15] The resulting calibration is z = 0.02362 and $\overline{E}_0 = 1767$ Mt .

Figure 3. Evolution of emissions and the ETS allowance surplus without the MSR



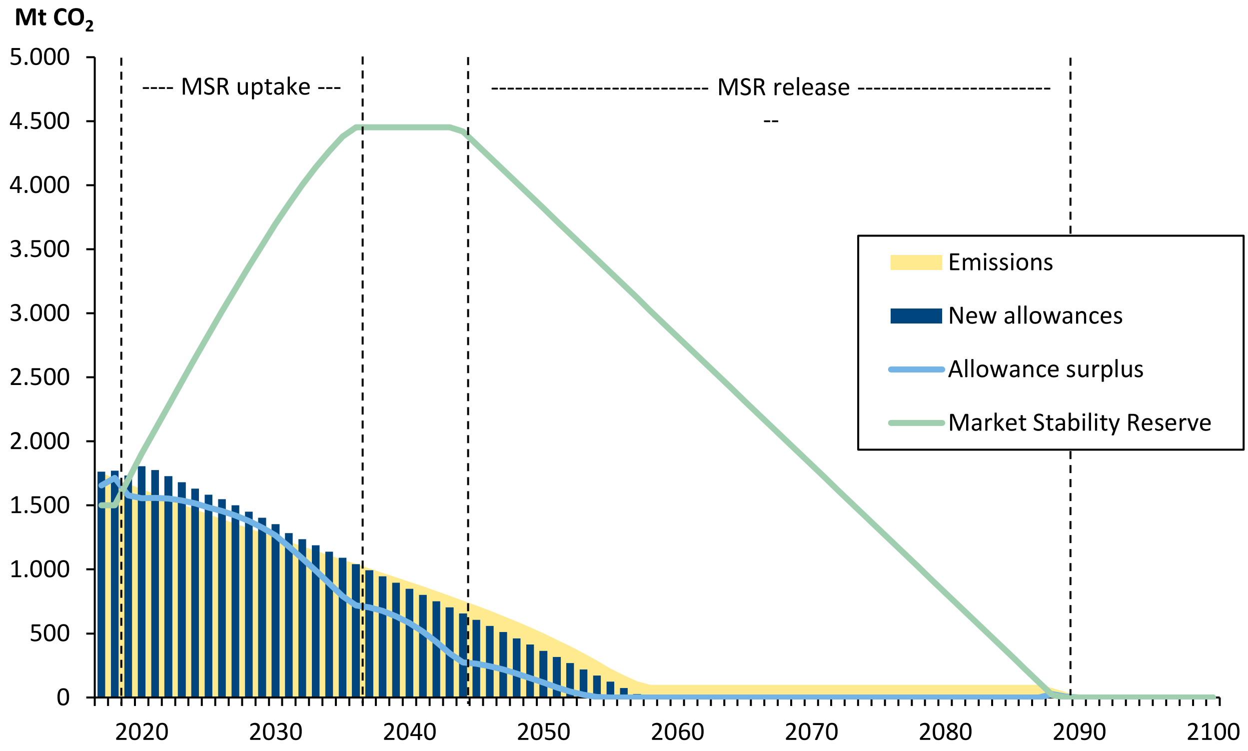
Note: Backloaded and unallocated allowances that will be injected into MSR are assumed here to be added to the allowance surplus in 2017.

Source: Own calculations based on the model described in Section 3.

For comparison, Figure 4 depicts how emissions and the allowance surplus available to the market would have evolved (according to our model) if the MSR rules agreed upon in 2015 had been maintained. We see that the MSR would have absorbed a large part of the allowance surplus that would otherwise emerge. The allowance surplus in Figure 4 peaks in 2018 and falls steadily in the subsequent years, partly because of the gradual fall in the issue of new allowances, and partly because of transfer of surplus allowances to the MSR. Nevertheless, the allowance surplus does not disappear until 2056. Moreover, the annual release of 100 million tons of allowances from the reserve when the surplus falls below 400 million tons means that emissions at an annual level of 100 million tons continue all the way up until 2096, due to an enormous allowance reserve accumulated until 2037 where the MSR peaks at around 5 billion tons. An important implication of the 2015 rules for the MSR is that a marginal annulment of allowances undertaken by a single

Member State in the coming years would not have reduced the aggregate allowance supply by a corresponding amount until after 2096.

Figure 4. Evolution of emissions and the ETS allowance surplus with the MSR rules agreed in 2015

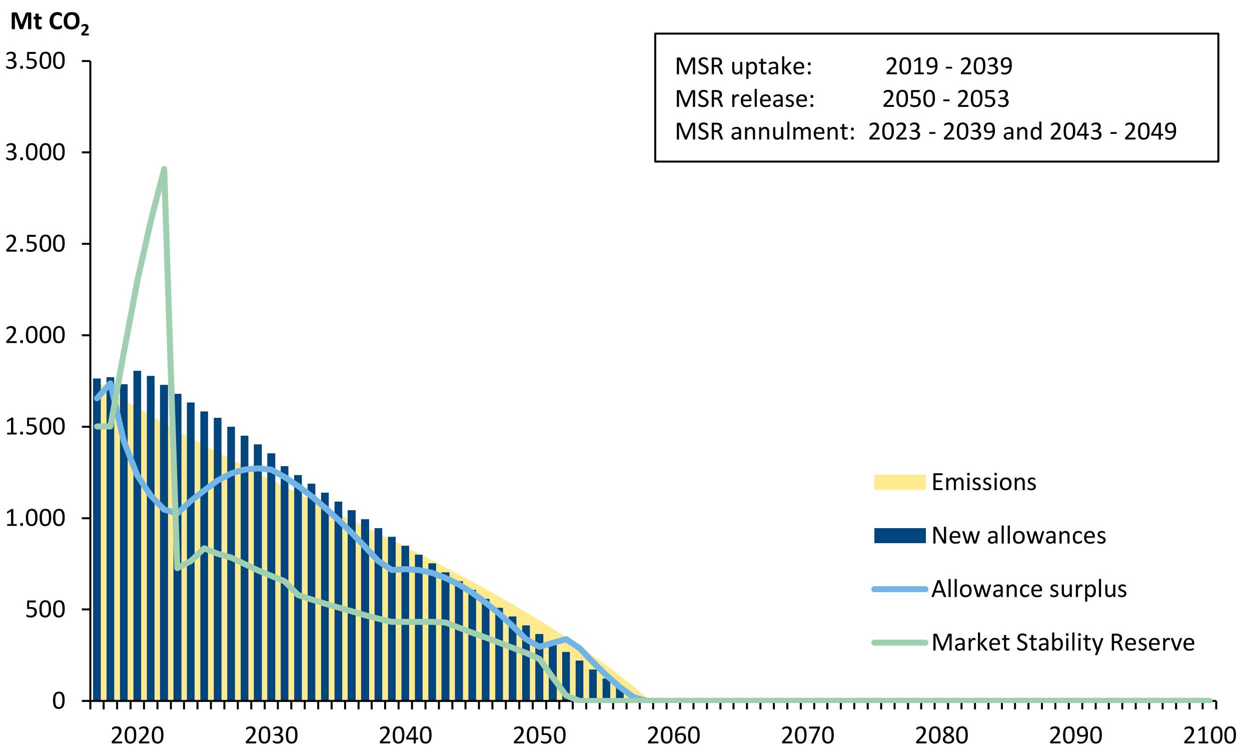


Source: Own calculations based on the model described in Section 3.

Figure 5 finally shows the predicted evolution of the allowance market following the 2018 ETS reform which introduced annulment of MSR allowances exceeding the previous year's auctions and a faster rate of transfer of allowances to the MSR from 2019 through 2023. The model simulation underlying Figure 5 accounts for the strong increase in the allowance price observed between 2017 and 2018. Our model can explain this price hike if we reduce the discount rate r from 10 percent to 7.44 percent. A fall in the required rate of return of this magnitude does not seem implausible, since the 2018 reform must have strengthened investor confidence in the future of the ETS, as discussed in section 3. Hence Figure 5 assumes $r = 0.0744$ but maintains the other parameter values underlying Figure 4. From Figure 5 we see that the new ETS rules will imply a large initial transfer of allowances to the MSR followed by a big chunk of annulments. According to our model the MSR will continue to absorb allowances for a twenty-year period until 2039, but from 2050 until 2053 the MSR will release allowances as the allowance surplus falls below the level of 400 Mt triggering releases. Again, the surplus is predicted to disappear around the mid-2050s.

Due to the new annulment mechanism a significant amount of allowances in the MSR will be annulled from 2023 until 2039 where the allowance surplus becomes so small that the MSR uptake stops. Since allowances transferred to the MSR are taken from the annual flow of auctioned allowances determining the allowance cap in the reserve, the ending of the MSR uptake after 2039 causes a temporary increase in the allowance cap which triggers a cessation of annulments until 2043. In that year the previous year's newly issued auctioned allowances fall to a level that reactivates the cap, resulting in a new round of annulments in the period 2043-2049.

Figure 5. Evolution of emissions and the ETS allowance surplus with the MSR rules agreed in 2018



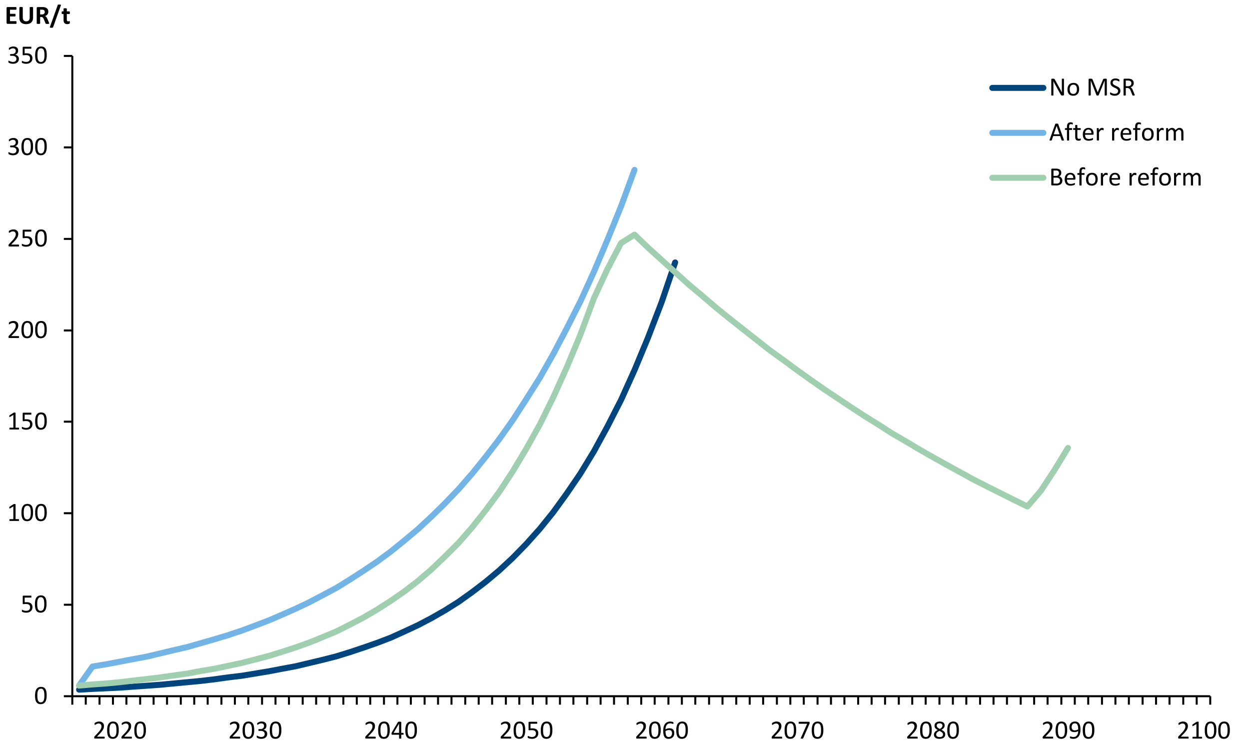
Source: Own calculations based on the model described in Section 3.

Note that the 2015 MSR rules would not have reduced the total accumulated volume of emissions but would only have shifted some emissions further into the future (which would of course have reduced the present value of accumulated emissions in case of positive discounting). By contrast, due to the new annulment mechanism, the 2018 ETS reform does reduce the accumulated undiscounted emissions, from 43,571 Mt to 38,597 Mt, representing an 11 percent cut. Nevertheless, it is striking that even after the 2018 reform the allowance surplus is still expected to persist until the mid-2050s as market participants react to the anticipated greater future scarcity of allowances by cutting their current emissions so as to save more allowances for future use.

Figure 6 shows the simulated evolution of the allowance price in the hypothetical case without the MSR and in our two reform scenarios. The diagram covers the period from 2017 until the year when the allowance surplus is eliminated. In the absence of the MSR the allowance price rises steadily at the required rate of return of 10 percent per year until the disappearance of the allowance surplus in 2062.[16] The 2018 reform causes an initial jump in the allowance price from 2017 to 2018. After that the price continues to rise at the more moderate required annual return of 7.44 percent until 2058 when the allowance surplus vanishes. If the MSR rules agreed in 2015 had instead been implemented, the presence of the MSR would have raised the allowance price until the disappearance of the allowance surplus in 2055. After that year the price would have started to fall, reflecting that the MSR would have released a constant supply of 100 Mt of allowances from the reserve each year while the continuing demand shift away from fossil fuels would tend to reduce the demand for allowances from year to year. In the early 2090s the allowance price would have recovered a bit as some investors would start to hold back allowances from the market in anticipation of further price increases as the MSR is emptied.

[16] The price paths illustrated in Figure 6 should be interpreted as underlying trends. Obviously our deterministic model cannot capture the stochastic shocks to the allowance market that would inevitably occur along the way.

Figure 6. Simulated evolution of the ETS allowance price (euros per ton CO_2)



Source: Own calculations based on the model described in Section 3.

One of the stated goals of the 2015 agreement on the MSR was to reduce the volatility of the allowance price. Using a simple partial equilibrium model of the ETS like the present one, Perino and Willner (2016) found that the 2015 MSR rules would in fact have increased the responsiveness of the price to shocks to the demand for allowances. However, the situation is different after the 2018 ETS reform. When we simulate the short-run effect on the allowance price of a temporary 1 Mt increase in allowance demand occurring in 2018, we find that the allowance price in 2018 would have increased by 0.19 percent under the 2015 MSR rules, whereas it would only increase by 0.03 percent under the new rules agreed in 2018. This is intuitive, since the annulment mechanism introduced by the 2018 reform means that a greater use of allowances in 2018 will lead to an almost corresponding reduction in the amount of allowances that will be annulled in 2023, so the increase in allowance demand will be met by an almost similar increase in the accumulated allowance supply.

Comparison with previous quantitative studies of ETS reform

In contrast to the picture painted in Figure 4, Perino and Willner (2016, p. 42) predict that the allowance surplus under the 2015 MSR rules would have disappeared already around 2036, even though they use a partial equilibrium simulation model of the ETS very similar to ours. In a subsequent paper, Perino and Willner (2017) have simulated the effects of an annulment mechanism like the one included in the 2018 ETS reform. Again, they foresee a relatively fast drop in the allowance surplus which implies that the annulment mechanism will be activated in a much shorter time span than in our 2018 reform scenario in Figure 5.

However, these studies by Perino and Willner do not allow for a gradual downward shift in the abatement cost function due to technical progress and structural change (in our notation, they set the parameter z in (21) equal to zero). Furthermore, Perino and Willner choose a value of our parameter b which implies a marginal abatement cost that is roughly nine times as high as in our calibration. Given their assumptions of a much higher underlying demand for allowances and a much higher marginal abatement cost, it is not surprising that they predict a much faster disappearance of the allowance surplus than we do. Perino and Willner base their calibration of b on a study by Landis (2015, Table 4), but the estimates of marginal abatement costs in that study are derived from simulations with a computable general equilibrium model, so the resulting cost estimate incorporates a host of general equilibrium effects that should not be included in an estimate of the parameter b in a single emissions equation like (4). Moreover, it does not seem reasonable to set the parameter z in (21) to zero, thereby implicitly ignoring the rapid technical progress in green energy technologies.

In a study undertaken on request from the Swedish government, the National Institute of Economic Research (2018) presents simulations of the effects of the annulment mechanism in the 2018 ETS reform based on a model very similar to the one set up by Perino and Willner (op.cit.) and by us. Unfortunately, the calibration of the model used by the NIER is poorly documented, but as far as we can deduce from the background paper by Carlén (2018, footnote 6), the NIER follows Perino and Willner in assuming that our parameter z is equal to zero. In any case, the policy conclusions drawn by the NIER suggest that they expect a scenario for the evolution of the allowance surplus rather similar to the one laid out in Perino and Willner (2016, 2017). We return to the policy implications in the next section.

To study the effects of the 2018 ETS reform, Beck and Kruse-Andersen (2018) set up their own partial equilibrium model of the allowance market. The demand for emission allowances is derived from the behaviour of a representative firm which maximizes the present value of its profits given by a profit function which is increasing in the level of emissions and in the relative efficiency of technologies for renewable energy production. The model allows the increase in this relative efficiency to be decreasing over time. Calibrating the model to match the ETS market situation in 2017, the authors project that the 2018 reform will imply an evolution of emissions and of the allowance surplus very similar to the one depicted in Figure 5. However, since their calibration implies a higher price sensitivity of allowance demand, and since they assume a rate-of-return requirement of only 5 percent, Beck and Kruse-Andersen simulate a much lower increase in the allowance price than illustrated in our Figure 6.

To test the sensitivity of our model forecasts to a stronger price response in our emissions function (4) we have carried out a simulation with a parameter value $b = 11.2$ five times as high as the one assumed in our base case (which follows the estimate of *b* made by Sandbag (2016b)). With this value of *b* we must recalibrate our parameters $\bar{E}_0$ and *z* to enable the model to replicate the market situation in 2017, maintaining the assumption of a discount rate of 10 percent prior to the 2018 reform. Given the resulting parameter values, it turns out that the discount rate must be lowered to 5.44 percent to account for the allowance price hike between 2017 and 2018. When simulating our model with these parameter values, we find that the allowance surplus disappears in 2051, slightly earlier than in the base case illustrated in Figure 5 where the surplus hits zero in 2058. However, the accumulated emissions in the scenario with a high *b*-value are actually a bit higher, amounting to 39,810 Mt, compared to 38,597 Mt in our base case.

The impression left by these studies and by our own analysis is that the assumption regarding technical progress in abatement technologies (as reflected in our parameter *z*) is crucial for the projected evolution of the future allowance surplus and future emissions, whereas other parameters such as the price sensitivity of allowance demand and the required rate of return are less important. As mentioned, our calibration of the *z*-parameter (see footnote 12) implies a reduction of future emissions which is consistent with the historical pattern since the establishment of the ETS. In the analysis below we will therefore maintain this calibration as our base case.

5. Effects of alternative climate national policies

Many EU member states have strived to reduce emissions from their ETS sectors through policies that reduce the demand for emission allowances such as national subsidies to renewable energy and, in some cases, carbon taxes or energy taxes that do not exempt the ETS sector. Under an alternative national policy, followed until recently by the Swedish government under the name of "utsläppsbromsen", a member state government may purchase ETS allowances and withdraw them from the market with the purpose of tightening the EU-wide emissions cap. A reduction of the emissions cap may also be achieved if the government abstains from auctioning some of the emission allowances allocated to it. In fact, several EU Member States will be allowed to meet part of their 2030 greenhouse gas reduction target for the non-ETS sector by auctioning a smaller amount of allowances within the ETS sector. Importantly, emission allowances that are cancelled as part of this so-called "flexibility mechanism" for meeting the non-ETS reduction target will still be counted as part of the total allowance surplus which may trigger an annulment of allowances due to the new cap on the MSR. By contrast, a national purchase and subsequent annulment of allowances that is not part of the non-ETS flexibility mechanism faces the risk that the resulting fall in the allowance surplus will cause fewer annulments of allowances in the MSR.

We will now use our model of the ETS to compare the effects of such national climate policies on the EU-wide CO_2 emissions. Drawing on our simulation results, we will also offer estimates of the national cost-effectiveness of the various policies. A policy such as subsidies to renewables that reduces the demand for allowances can be modelled as a one-time downward shift in our parameter $\bar{E}_0$ in the emissions function (4). For convenience, we will refer to this type of policy as "demand reduction". A national annulment policy such as the Swedish "utsläpsbromse" may be modelled as a one-time reduction in newly issued allowances, i.e., a cut in our variable Q_0 which triggers endogenous subsequent changes in the MSR uptake and release of allowances as well as changes in the number of MSR allowances that are annulled. We will refer to this policy as "annulment". Finally, we may model a national annulment of allowances under the non-ETS flexibility mechanism (i.e., abstention from auctioning of allowances) as an exogenous decrease in the accumulated allowance issues Q_T^a defined in (12) which does not affect the number of allowances transferred to or released or annulled from the MSR. We will call this policy "annulment FM", where "FM" stands for "Flexibility Mechanism".

Effects of national climate policies on CO_2 emissions

Table 1 shows how effective the three alternative national climate policies are in reducing the accumulated CO_2 emissions within the ETS, measured by the Coefficients of Emission Reduction (*CER*) defined in (13) and (14), using a modest 1 percent annual discount rate when discounting future emissions. The table highlights the great importance of the new annulment mechanism in the MSR. For example, the figure at the bottom of the first column shows that the accumulated emissions in 2060 (measured in present value terms) will be reduced by 94 percent of the emissions cut achieved through a renewables subsidy that reduces the demand for allowances in 2020. In other words, since this policy measure will increase the allowance surplus, thus increasing the number of allowances transferred to the MSR and thereby causing more allowances to be permanently cancelled, only 6 percent of the initial cut in emissions will be offset by higher emissions elsewhere in the ETS sector.

By contrast, according to the fourth column in Table 1 an annulment of allowances undertaken by an individual EU member state in 2020 will only reduce the accumulated emissions in 2060 by 5 percent of the initial annulment, since the cancellation of allowances undertaken at the member state level will be largely offset by fewer cancellations of allowances held in the MSR, as the initial drop in the allowance surplus will cause fewer transfers of allowances to the reserve.

Table 1: Coefficients of Emissions Reduction after the 2018 ETS reform ($\rho = 1\%$)

Policy horizon (*H*)	Demand reduction undertaken in:			Annulment undertaken in:			Annulment FM undertaken in:		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
2030	0.98	0.92	0.88	0.00	0.01	0.00	0.08	0.05	0.01
2040	0.97	0.90	0.84	0.01	0.03	0.05	0.22	0.19	0.15
2050	0.95	0.86	0.75	0.03	0.07	0.13	0.48	0.45	0.41
2060	0.94	0.80	0.63	0.05	0.13	0.25	0.83	0.81	0.77

Note: The table considers policy experiments where 1 million allowances are annulled; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2, given the initial allowance price. The numbers show the present value in 2018 of the change in emissions occurring up until year *H.*
Source: Own calculations based on the model described in Section 3.

However, since member state annulments undertaken under the so-called flexibility mechanism will not reduce the recorded allowance surplus that governs the dynamics of the MSR, this policy will in fact succeed in reducing emissions considerably in the long run, as shown in the last three columns in Table 1. Still, we see that for policy horizons up until 2050 where annulment under the flexibility mechanism only works by driving up the allowance price via a cut in the allowance surplus, this policy is much less effective in cutting emissions than a policy that reduces the demand for allowances.

Sensitivity analysis

The overall impression from Table 1 is that national subsidies or carbon taxes to promote renewable energy are generally more effective in reducing CO_2 emissions from the ETS sector than annulments of emissions allowances undertaken by individual EU governments. Table 2 shows that this conclusion holds when future emissions are discounted at an annual rate of 1 percent or more, based on the considerations in section 2. For a zero discount rate, we see that annulment of allowances under the flexibility mechanism does in fact generate a larger fall in accumulated emissions in the very long run than a policy of demand reduction. The reason is that annulment under the flexibility mechanism reduces the accumulated supply of allowances both directly and indirectly by driving up the allowance price during the long initial phase with an allowance surplus. This price increase reduces emissions, thereby increasing the allowance surplus and inducing larger transfers of allowances to the MSR which in turn causes more cancellations of allowances in the reserve. This is another example of the importance of the new annulment rules for the MSR.

Table 2: Coefficients of Emissions Reduction after the 2018 ETS reform: Sensitivity to the discount rate for future emissions (ρ) for a policy change in 2020

Policy horizon (H)	Demand reduction			Annulment			Annulment FM		
	ρ = 0%	ρ = 1%	ρ = 2%	ρ = 0%	ρ = 1%	ρ = 2%	ρ = 0%	ρ = 1%	ρ = 2%
2030	1.00	0.98	0.96	0.00	0.00	0.00	0.09	0.08	0.07
2060	0.94	0.94	0.93	0.06	0.05	0.03	1.11	0.83	0.63

Note: The table considers policy experiments where 1 million allowances are annulled; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2, given the initial allowance price. The numbers show the present value in 2018 of the change in emissions occurring up until year H.
Source: Own calculations based on the model described in Section 3.

The sensitivity of our results to a stronger response of emissions to the allowance price is illustrated in Table 3 where we have set our price sensitivity parameter *b* at a value five times as high as in our baseline scenario in Table 1.[17] We see that even with this significant recalibration of the model, a policy that reduces the demand for allowances is still a far more effective way of reducing emissions than annulment of allowances at the national level, unless the annulment is undertaken within the flexibility mechanism (which only allows annulments within fairly narrow limits) and policy makers adopt a rather long time horizon.

Table 3: Coefficients of Emissions Reduction after the 2018 ETS reform: Sensitivity to the price response of emissions (*b*) for a policy change in 2020 ($\rho = 1\%$)

Policy horizon (*H*)	Demand reduction		Annulment		Annulment FM	
	b = 2.2	*b* = 11.2	*b* = 2.2	*b* = 11.2	*b* = 2.2	*b* = 11.2
2030	0.98	0.95	0.00	0.03	0.08	0.18
2060	0.94	0.85	0.05	0.13	0.83	0.88

Note: The table considers policy experiments where 1 million allowances are annulled; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2, given the initial allowance price. The numbers show the present value in 2018 of the change in emissions occurring up until year *H*.
Source: Own calculations based on the model described in Section 3.

Table 4 finally shows the effects on the Coefficients of Emissions Reduction of assuming a significantly lower market discount rate *r* than in our baseline case. The low discount rate of 2.92 percent in the table was derived from the same two-step calibration procedure as the one used in our baseline: In the first step we assumed $r = 0.04$ and $b = 2.2$ and calibrated the values of $\overline{E}_0$ and *z* to enable the model to reproduce the emissions and the average allowance price observed in 2017. In the second step we reduced the value of *r* from 4 percent to 2.92 percent to enable the model to explain the allowance price hike between 2017 and 2018. We see that the low market discount rate and the implied lower rate of allowance price increase during the long phase with an allowance surplus makes an annulment policy even less effective compared to a policy of demand reduction.

[17] As mentioned in section 4, when we raise the value of *b*, we recalibrate the other parameters in the model so that is still reproduces the initial market situation.

However, if the annulment exploits the flexibility mechanism, it becomes slightly more effective than the demand reduction in the very long run.

Table 4: Coefficients of Emissions Reduction after the 2018 ETS reform: Sensitivity to the market discount rate (*r*) for a policy change in 2020 ($\rho = 1\%$)

Policy horizon (*H*)	Demand reduction		Annulment		Annulment FM	
	r = 2.92%	r = 7.44%	r = 2.92%	r = 7.44%	r = 2.92%	r = 7.44%
2030	0.98	0.98	0.00	0.00	0.21	0.08
2060	0.98	0.94	0.00	0.05	1.09	0.83

Note: The table considers policy experiments where 1 million allowances are annulled; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2, given the initial allowance price. The numbers show the present value in 2018 of the change in emissions occurring up until year *H*.
Source: Own calculations based on the model described in Section 3.

The quantitative effects of alternative national climate policies reported above are rather similar to the estimates presented by Beck and Kruse-Andersen (2018) even though they use a different model of the ETS and do not discount future emissions. Like us, they estimate that the new annulment mechanism in the MSR will remain operative until around 2038. On this basis they conclude that a national policy of demand reduction will be far more effective in reducing emissions than annulment of allowances at the national level (when annulment is not undertaken as part of the flexibility mechanism), as long as the national policy measures are undertaken during the 2020s. However, if a significant part of the national policy measures are implemented after 2038 where the new annulment mechanism in the MSR will only be activated for a few further years, a national annulment policy may become more effective than a policy that reduces the demand for allowances.

The National Institute of Economic Research (2018) also acknowledges that national demand-reducing policies may reduce the accumulated EU-wide CO_2 emissions due to the new MSR annulment mechanism, but because they expect a much faster elimination of the allowance surplus than we do, the NIER believes that no annulments will take place after the mid-2020s. They therefore argue that, rather than undertaking demand-reducing policies, it will be more cost-effective if the Swedish government purchases ETS allowances in the market and postpones their cancellation until the MSR annulment mechanism is no longer operating to secure a long-run reduction in total allowance supply. We find this idea intriguing, since it would seem to imply that a national policy of general annulments could be designed to generate the same effects as annulment under the flexibility mechanism. However, since the NIER does not allow for the underlying trend towards lower emissions (they seem to set our parameter z equal to zero), we believe that they significantly underestimate the time it will take for the allowance surplus to vanish. In our baseline scenario and in the base case considered by Beck and Kruse-Andersen (2018), the MSR annulment mechanism remains active until the end of the 2030s, so the revised "utsläpsbromse" proposed by the NIER would not have a significant impact on emissions until after that time.[18]

The cost-effectiveness of alternative national climate policies

The analysis above suggests that, in physical terms, expansion of renewable energy production via subsidies may be a more effective way of cutting emissions than annulment of emission allowances within the ETS. But is expanding renewable energy supply also the more *cost-effective* climate policy? We may use our cost-effectiveness formulas (18) and (19) to answer this question, applying them to the case of Denmark. For this purpose we need estimates of the allowance price p and of the renewables subsidy $c^R - q$ prevailing in the year of the policy intervention which is 2020, 2025 or 2030 in Table 5 below. We use the values of p predicted by our model for those years and estimate the subsidy rate $c^R - q$ from the feed-in tariff granted to power produced by the most recent large Danish offshore wind farm, converting the subsidy granted per kWh into the subsidy rate needed to crowd out 1 ton of CO_2, based on an estimate of the energy mix (coal, natural gas and biomass) in the marginal unit of electricity supplied to the Danish electricity market. The resulting estimate of the subsidy needed to increase the supply of offshore wind is 4.0 euros per ton CO_2. We assume conservatively that the same subsidy is required for all of the years 2020, 2025 and 2030, although the expected rise in the allowance price is likely to reduce necessary subsidy. Our model estimates of the future allowance prices in the three years mentioned are 18.8 EUR/ton, 27.0 EUR/ton and 38.6 EUR/ton, respectively.

In principle, the use of our cost-effectiveness formulas (18) and (19) also requires an estimate of the price elasticity ε_1 (which can be calculated from our model) and a forecast for the time series

[18] In our simulations there is even a renewed spell of annulments of allowances in the MSR in the period 2043-49, so the "utslipsbromse" would not be effective in that period either.

$\left(Q_t^d - F_t^d\right)/\tilde{Q}_1$. In the case of a large EU country it may be important to account for the latter magnitude which captures the terms-of-trade effect of changes in the allowance price, but in Denmark the estimated net import of allowances (emissions minus allocations) was only about 0.15 percent of the total volume of allowances available to the ETS market in 2015. Hence the terms-of-trade effect for Denmark is tiny and we therefore neglect it, thereby avoiding having to make un uncertain forecast for $\left(Q_t^d - F_t^d\right)/\tilde{Q}_1$.

With these estimates and assumptions, and using the values for the Coefficients of Emission Reduction in Table 1, we obtain the estimates of social costs per unit of effective emission reduction reported in Table 5 for different policy horizons and different timings of the policy interventions.

Table 5: The cost-effectiveness of alternative national climate policies after the 2018 ETS reform (cost in euros of reducing accumulated discounted emissions by 1 ton, $\rho = 1\%$)

Policy horizon	Demand reduction undertaken in:			Annulment undertaken in:			Annulment FM undertaken in:		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
2030	4.1	4.3	4.5	4,329.1	3,321.9	11,980.6	235.1	534.2	3,914.4
2040	4.1	4.4	4.7	1.583.6	883.4	784.6	86.0	142.1	256.3
2050	4.1	4.6	5.3	727.5	374.0	287.0	39.5	60.1	93.8
2060	4.2	4.9	6.2	415.7	207.8	152.7	22.6	33.4	49.9

Note: The table considers policy experiments where 1 million allowances are annulled; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2, given the initial allowance price. The calculations are based on the estimates of the *CER* in Table 1 and the measures of cost effectiveness (18) and (19), but we ignore the terms-of-trade effects since they will be negligible in a small economy. The numbers reflect an estimate of the average 2018 allowance price and the 2018 cost of subsidizing off-shore wind energy in Denmark.
Source: Own calculations based on the model described in Section 3.

We see that for policy horizons up until 2060 and for all timings of the policy intervention up until 2030 the subsidy policy is by far the most cost-effective policy even under our conservative assumption that the required renewables subsidy cannot be scaled down during the coming decade due to technical progress in green technologies and a rising allowance price. In particular, since the two annulment policies reduce emissions by very little in the short and medium term, and since the allowance price rises considerably towards 2030, these policies are very costly unless the policy horizon is very long. Moreover, because of the rising allowance price, even the annulment policy under the flexibility mechanism remains far more costly than the subsidy policy, despite the fact that the former policy is quite effective in reducing emissions in the long run.

The estimates in Table 5 are of course sensitive to parameter values, but the cost advantage of a policy of demand reduction (on this side of 2030) seems so robust that it is unlikely to be overturned by any plausible changes in parameters. However, it should be stressed that we are measuring the cost-effectiveness of climate policies from a national perspective and that national climate policies towards the ETS sector may compromise the cost-effectiveness of EU climate policy. More precisely, if EU member state *i* offers a subsidy at the rate s^i per unit of emissions reduction in the domestic ETS sector, and the abatement cost function is given by (2), one can show (see Appendix A) that the marginal abatement cost of country *i* in year *t* (MAC_t^i) will be given by

$$MAC_t^i = p_t + s_t^i. \tag{21}$$

If member states offer different subsidy rates, it follows from (21) that their marginal costs of abatement will differ in which case the total EU-wide abatement costs will not be minimized. Against this background it is clearly preferable if the total EU-wide emissions reduction can be attained solely via a common carbon price established through a common cap-and-trade system rather than through a relatively low ETS allowance price combined with differing national subsidies or differing national carbon taxes. However, the national climate policies directed at the ETS sector indicate that some EU member states do not find that the ETS delivers sufficient emissions reductions. This observation takes us to the political economy of the ETS.

6. Some reflections on the political economy of the ETS

The decision by EU policy makers to supplement the ETS by a Market Stability Reserve from 2019 may be seen as a reaction to the growing allowance surplus and the resulting very low allowance price. At the same time the lack of political will to drive the allowance price up to a level that could make subsidies to renewable energy redundant indicates that EU policy makers are reluctant to accept high energy prices, perhaps because of concerns about the international competitiveness of EU firms or because of fear of negative voter reactions.

These observations suggest that the total supply of emission allowances may be determined in a political process at the EU level which trades off the environmental benefits of lower CO_2 emissions against the non-environmental benefits of low energy prices. To illustrate the possible implications of this hypothesis for the effectiveness of national climate policies, let us assume for concreteness that EU policy makers adjust the aggregate supply of emission allowances as if they were trying to minimize a social loss function of the simple quadratic form

$$SL = \frac{1}{2}V_1^2 + \frac{\alpha}{2}p_1^2, \qquad \alpha > 0, \tag{22}$$

where V_1 is the present value of CO_2 emissions, and α is a parameter reflecting the intensity of political preferences for low allowance prices relative to the preference for low emissions. We will assume that the policy horizon does not extend beyond the year when the emissions cap becomes binding.[19] In that case it follows from (5) that future allowance prices are proportional to the current allowance price p_1, since (5) implies that $p_t = (1+r)^{t-1} p_1$, and hence we do not need to incorporate them explicitly in the loss function (22), since any concern about future allowance prices is reflected in the size of the parameter α. Notice also that the size of α will reflect a weighted average of the preferences of individual EU member states, with weights depending on the cross-country distribution of votes in EU decision-making bodies.

In Appendix C we use the model of the ETS set up in section 3 to show that if EU policy makers seek to minimize the social loss function (22), they will react to member state annulments of emission allowances by undertaking a fully offsetting increase of allowance supply at the EU level so as to keep the total allowance supply unchanged at the loss-minimizing level. In this way annulments at the national level become completely ineffective in reducing EU-wide emissions. As we have seen in the previous section, the new annulment mechanism in the MSR does indeed tend to make national annulments ineffective. This is consistent with our hypothesis that EU policy makers act as if they are trying to strike an optimal political balance between emission reductions and a low allowance price.

Appendix C also shows that this behaviour implies that national policy initiatives to increase the supply of renewable energy will only be partially offset by a tightening of the total allowance supply at the EU level. National policies that reduce the demand for allowances will therefore succeed in reducing total EU emissions to some extent. Again, this is consistent with our simulated effects of the MSR rules. The intuition for this result is the following: by reducing emissions at any given allowance price, an increase in renewable energy supply improves the trade-off between the

[19] This does not seem implausible since our simulations suggest that the allowance surplus does not vanish until some time in the 2050s. For the moment, the EU does not have a stated target for climate policy that goes beyond 2050.

policy goal of lower emissions and the goal of a lower energy price. EU policy makers choose to realize the resulting welfare gain partly in the form of lower emissions and partly in the form of a lower energy price (a lower allowance price).

In summary, on the plausible assumption that EU policy makers care about the level of energy prices as well as the level of emissions, the (simplistic) political economy analysis in this section supports the hypothesis that subsidies to renewable energy are a more effective way of reducing emissions than annulment of emission allowances at the individual member state level. It also suggests that there are limits to the politically acceptable fluctuations in the allowance price. This raises the question whether the design of the ETS can be improved from an economic efficiency viewpoint in a way that is politically realistic. The next section will discuss this issue.

7. Proposal for an efficiency-improving ETS reform

Fortunately, it is possible to accommodate the apparent political desire for limited fluctuations in the price of emission allowances in a way that increases economic efficiency compared to a situation with a pure cap-and-trade system. However, the MSR rules for the ETS are hardly the best way of trading off the desire for control of emissions against the desire for a stable allowance price. For one thing, the complex MSR rules are rather intransparent, but more fundamentally, they do not target price stability directly, since changes in the allowance supply are triggered by the lagged changes in the allowance surplus rather than by fluctuations in the current market price. Drawing on the literature on optimal pollution control, this section presents a blueprint for a future ETS reform that replaces the MSR by a simpler mechanism to stabilize the allowance price.

Pollution control: prices versus quantities

When there is complete certainty about the marginal damage cost curve and the marginal abatement cost curve, a regulator can implement the optimal level of pollution either by controlling the quantity of emissions directly via a cap-and-trade system where the emissions cap is set at the optimal level where the marginal damage cost equals the marginal abatement cost, or by controlling the price of emissions via an emissions tax equal to the marginal damage cost at the optimal level of pollution. Under the emissions tax, cost-minimizing firms will then emit up to the point where their marginal abatement costs are equal to the emissions tax rate, thereby producing the same result as the cap-and-trade system.

If there is uncertainty about the position of the marginal damage cost curve, it is well-known that a cap-and-trade system will still deliver the same quantity and price of pollution as an emissions tax, but in this case the actual pollution level will exceed the optimal level if the regulator underestimates the marginal damage cost, and vice versa (see Phaneuf and Requate (2017, p. 49)).

However, when uncertainty centers on the position of the marginal abatement cost curve, the choice between the two modes of pollution control matters. In a seminal paper, Weitzman (1974) showed that if the marginal damage cost curve is flatter than the marginal abatement cost curve, an emissions tax is preferable to a cap on the quantity of emissions, and vice versa. With a flat marginal damage cost curve it is not so important to keep the quantity of emissions close to the optimal level, and at the same time a miscalculation of the position of the marginal abatement cost curve could cause a large deviation of abatement costs from their optimal level if the marginal abatement cost curve is steep. Hence it is better to fix the price of emissions via an emissions tax, thereby controlling the marginal abatement cost, rather than controlling the quantity of emissions through a cap-and-trade system.

Many economists (e.g., Nordhaus (2007)) have argued that while the marginal cost of abating CO_2 emissions is related to the current level of emissions and is therefore sensitive to the amount of emissions reduction, the marginal social cost of emitting an extra ton of CO_2 is largely independent on the current level of emission since it depends on the accumulated stock of CO_2 in the atmosphere. This observation suggests that the slope of the marginal damage cost curve is indeed flatter than the slope of the marginal abatement cost curve, so according to Weitzman's analysis it is preferable to control CO_2 emissions via a carbon tax rather than via a cap-and-trade system. When the marginal abatement cost curve shifts back and forth over time, a price policy (carbon tax) allows firms to shift their abatement efforts from periods with high marginal abatement costs to periods where marginal abatement costs are low without compromising the government's ability to control (at least approximately) the accumulated emissions in the longer run via an appropriate choice of the level of carbon tax. Newell and Pizer (2003) present a rigorous analysis of this issue in a model that explicitly accounts for the fact that the damage costs of climate change depend on the stock of CO_2 in the atmosphere. They show that, for plausible parameter values, the expected present value of the sum of the total damage cost and the total abatement cost will be lower under the optimal carbon tax than under the optimal quantity policy (the optimal cap-and-trade system). Pizer (2002) estimates that the expected welfare gain from the optimal carbon tax policy is about five times higher than the gain from the optimal quantity policy.

In summary, if policy makers have to choose between a carbon tax and a pure cap-and-trade system, addressing climate change via the carbon tax seems preferable.

The superiority of a mixed system

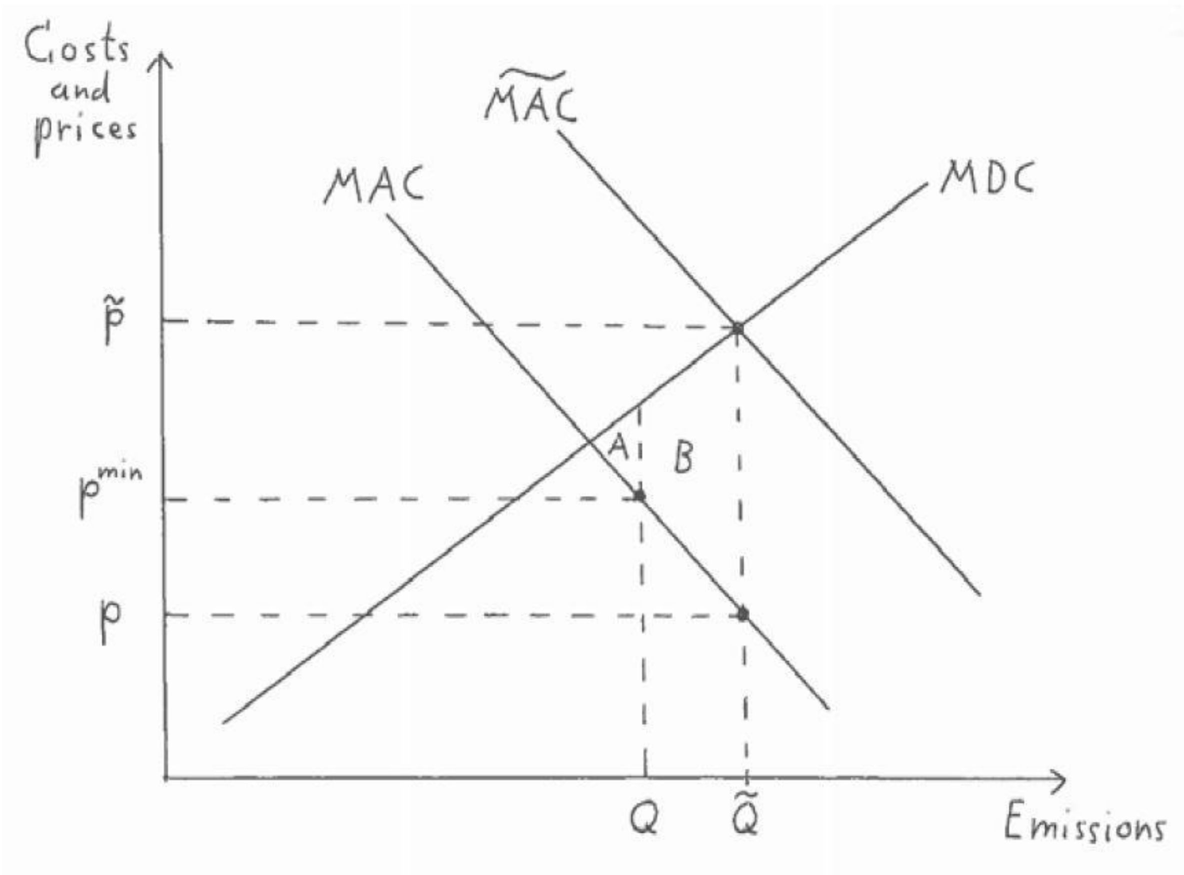
However, a large strand of literature starting with the contribution by Roberts and Spence (1976) has suggested that a mixed system combining tradeable emissions allowances with a minimum and a maximum allowance price would be more efficient than a pure tax scheme or a pure cap-and-trade scheme. In practice such a mixed system could be implemented through an auctioning procedure for emission allowances that includes a minimum price as well as a maximium price for auctioned allowances. If the bidding price of allowances hits the price floor, the issue of allowances is reduced to the degree needed to sustain the minimum price, and if the bidding price hits the price ceiling the allowance issue is expanded to prevent the allowance price from exceeding the maximum price. As Roberts and Spence (op.cit.) showed, such a mixed system is more efficient because it imposes a penalty scheme on polluters which approximates the marginal damage cost curve better than a pure tax scheme or a pure cap-and-trade system.

Over the years numerous authors have advocated variants of the mixed system proposed by Roberts and Spence, sometimes including only a price floor or a price ceiling.[20] Contributions to this literature include Weitzman (1978), McKibbin and Wilcoxen (1997), Pizer (2002), Jacoby and Ellerman (2004), Newell et al. (2005), Murray et al. (2009), Burtraw et al. (2010), Fell (2016), and Kollenberg and Taschini (2016) among many others. Figures 4 and 5 offer a simple illustration of the potential for efficiency gains from a scheme of pollution control that mixes price and quantity control.

Figure 7 shows how a minimum allowance price set at the level $p^{\min}$ can increase welfare when abatement costs are overestimated. The regulator's best estimate of the marginal damage cost of emissions is represented by the curve MDC. The regulator further believes that the marginal abatement cost curve is given by the curve MAC, so under a pure cap-and-trade scheme he would set the allowance supply at Q corresponding to his estimate of the optimal emission level where the marginal abatement cost equals the marginal damage cost.

[20] Hepburn (2006) provides a thorough review of the many issued involved in designing a mixed system.

Figure 7. The welfare gain from a minimum allowance price

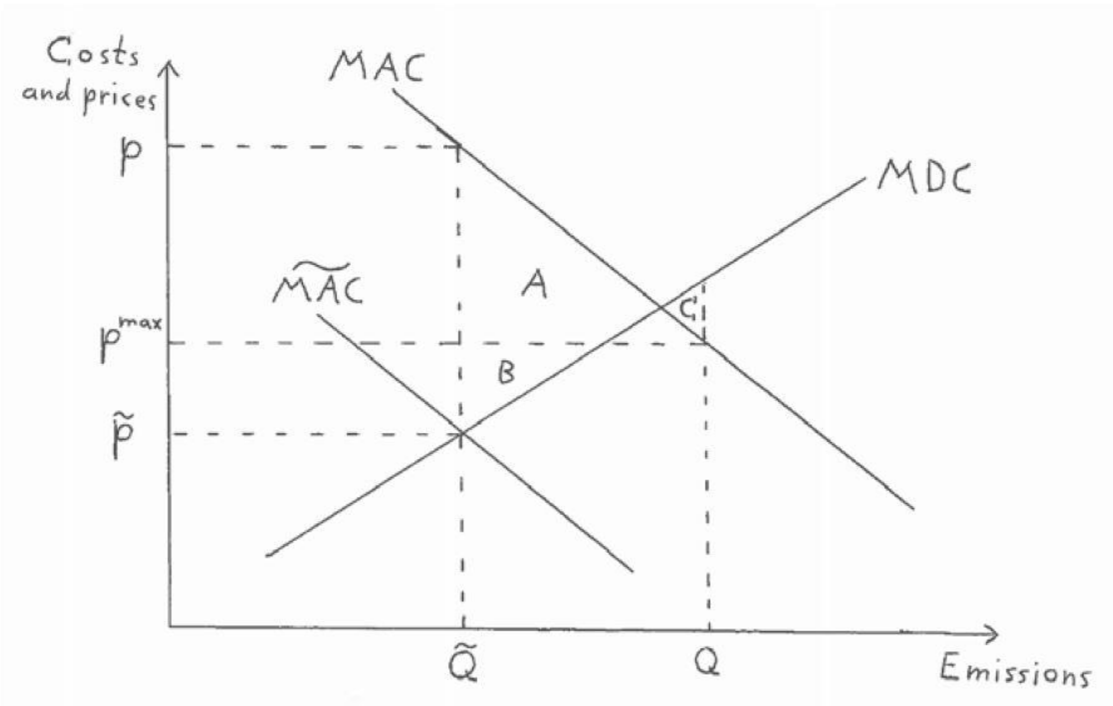


But given the actual MAC curve (the lower curve in the diagram), an allowance supply of Q would drive the allowance price down to *p*, since cost-minimizing firms abate until their marginal abatement cost equals the allowance price which will therefore have to settle at the level *p* to equate allowance demand with allowance supply. Such a low allowance price would create a welfare loss equal to the sum of areas A and B because of too little abatement compared to the optimal level.[21] With a minimum price $p^{\min}$ the allowance supply would be reduced to Q when the bidding price hits this level, and the welfare loss from the underestimation of abatement costs would be reduced to area A. More generally, any minimum price below the perceived optimal price level $\tilde{p}$ and above *p* would bring actual emissions closer to the optimal level, thus helping to reduce the welfare loss from the regulator's imperfect information.

[21] The area under the MDC curve measures the total damage cost, and the area under the MAC measures the total abatement cost. Hence the sum of the areas A and B in Figure 7 measures the excess of the total damage cost over the total abatement cost resulting from the excess pollution caused by the overestimation of the true abatement cost.

Figure 8 illustrates the opposite case where the regulator underestimates marginal abatement costs, believing them to be given by the curve MAC while in fact they are given by the curve MAC. Under a pure cap-and-trade scheme the regulator would set the allowance supply at Q which would imply a permit price of *p* and a welfare loss equal to area A+B stemming from excessive abatement.

Figure 8. The welfare gain from a maximum allowance price



But with a ceiling p^{max} for the price of auctioned emission allowances, the allowance supply would be expanded to Q, and the welfare loss from the resulting slightly excessive emission level would be area C which is much smaller than area A+B. In fact, any maximum allowance price below *p* and above $\tilde{p}$ would help to reduce the welfare loss from underestimation of abatement costs.

In short, the price floor and the price ceiling serve as “safety valves” that prevent the allowance price from drifting too far away from the true marginal social cost of pollution, thereby helping to reduce the welfare loss from imperfect information about abatement costs.

Caveats

We argued above that a minimum and a maximum price of ETS allowances would be compatible with the revealed political preference for avoiding allowance prices that are “too low” or “too high”. But our proposal for further ETS reform may run into other difficulties raised by EU law and politics such as those mentioned by Hepburn et al. (2016). First, it would be important that a floor and a ceiling for the ETS allowance price is not seen as a measure “primarily of a fiscal nature”, since that would require an unlikely unanimous approval in accordance with article 192 §2 of the Lisbon Treaty. Since the current rules for the ETS already have fiscal implications which would not be fundamentally changed by a transition to the mixed system described above, we find it hard to see why a transition to such a system with limit prices on auctioned allowances should trigger article 192. A second and potentially more serious obstacle is that the mixed system would require agreement on the minimum and maximum allowance prices by a qualified majority of EU member states. Perhaps the greater transparency of a system with explicit minimum and maximum prices is harder to agree on than the setting of the thresholds for the uptake, release, and annulment of allowances in the MSR.

Another concern is the one voiced by Salant (2016) who points out that uncertainty about the future rules for the ETS creates higher costs of achieving a given target for emissions reductions. A proposal for further reform of the system following years of hard bargaining over the MSR rules recently agreed could create renewed uncertainty which could reduce the efficiency of the market for allowances. However, since the recent ETS reform does not address the problem of price instability in the most direct and effective way, and since the ETS is likely to operate for several decades to come, we expect that the debate on the design of the system will continue. In any case, the new rules for the ETS agreed in 2018 do not seem sufficiently ambitious in the light of the 2015 Paris agreement which will require all regions in the world to undertake much faster emissions reductions than currently planned if the target of keeping global warming well below 2 degrees Celsius is to be met. We therefore anticipate that new opportunities for reform of the ETS will arise in the future and recommend that the complex and intransparent MSR rules be replaced by a floor and a ceiling for the allowance price when the next occasion for reform arises.

8. Conclusions

The analysis in this paper leads to five main conclusions:

First, in the absence of further reform the surplus of emission allowances within the ETS is likely to persist for several decades. For a long time the system will therefore work differently than a textbook cap-and-trade system with a binding cap.

Second, the new Market Stability Reserve taking effect from 2019 is a fundamental change to the system that will endogenize the total supply of emission allowances. As a consequence, national policy measures that reduce the demand for allowances may permanently reduce total EU-wide emissions.

Third, for an EU member state that wishes to take the lead in climate policy, a policy that promotes renewable energy will be a far more cost-effective way of reducing EU-wide emissions from the ETS sector than a policy of annulling emission allowances.

Fourth, the endogeneity of allowance supply built into the new Market Stability Reserve may be explained by a political economy model where EU policy makers trade-off a desire to cut emissions against a desire to keep energy prices for EU businesses and households low. Proposals for future ETS reform should account for the fact that such political forces are likely to be at play.

Fifth, when the next occasion for reform of the ETS arises, policy makers should turn the system into a mixture of price and quantity control by introducing a minimum and a maximum price of emission allowances. This will improve the efficiency of the system and make the complex and intransparent rules for the Market Stability Reserve redundant.

References

Arrow, K.J, M.L. Croppery, C. Gollier, B. Groom, G.M. Heal, R.G. Newell, W.D. Nordhaus, R.S. Pindyck, W.A. Pizer, P.R. Portney, T. Sterner, R.S. J. Tol and M.L. Weitzman (2014). Should governments use a declining discount rate in project analysis? *Review of Environmental Economics and Policy* 8, 145-163.

Beck, U.R. and P. K. Kruse-Andersen (2018). Endogenizing the cap in a cap-and-trade system: assessing the agreement on EU ETS phase 4. Working Paper 2018:2, Danish Economic Councils.

Böhringer. C., H. Koschel and U. Moslener (2008). Efficiency losses from overlapping regulation of EU carbon emissions, *Journal of Regulatory Economics* 33, 299-317.

Böhringer. C., A. Löschel. U. Moslener and T. Rutherford (2009a). EU climate policy up to 2020: An economic impact assessment, *Energy Economics* 31, S295-S305.

Böhringer. C.. T. Rutherford and R. Tol (2009b). The EU 20/20/2020 targets: An overview of the EMF22 assessment, *Energy Economics* 31, S268–S273.

Boeters. S. and J. Koornneef (2011). Supply of renewable energy and the cost of EU climate policy, *Energy Economics* 33, 1024-1034.

Burtraw, D., K. Palmer, and D. Kahn (2010). A symmetric safety valve. *Energy Policy* 38, 4291-4932.

Carlén, B. (2018). EU ETS och automatisk annullering av utsläpsrätter. Konjunkturinstitutet, KI-NR 2018:9.

Carlén, B., A. Dahlqvist, S. Mandell, and P. Marklund (2018). EU ETS emissions under the cancellation mechanism: effects of national measures. National Institute of Economic Research (Konjunkturinstitutet), Working Paper No. 151, June 2018.

Danish Council on Climate Change (2017). Det oppustede CO_2-kvotesystem. Klimarådet, marts 2017. (file:///C:/Users/kzj109/Downloads/analyse_af_kvotemarkedet_final%20(4).pdf)

Eichner, T. and R. Pethig (2009). Efficient CO2 emissions control with emissions taxes and international emissions trading, *European Economic Review* 53, 625–635.

Ellerman, A.D., C. Marcantonini, and A. Zaklan (2016). The European Union Emissions Trading System: ten years and counting. *Review of Environmental Economics and Policy* 10, 89-107.

European Commission (2017). *Report from the Commission to the European Parliament and the Council on the functioning of the European carbon market.* November 2017.

Fell, H. (2016). Comparing policies to confront over-allocation. *Journal of Environmental Economics and Management* 80, 53-68.

Gerlagh, R. (2011). Too Much Oil. *CESifo Economic Studies* 57: 79–102.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82, 48-88.

Gronwald. M. and B. Hintermann (2015). The EU ETS, Ch. 1 in M. Gronwald and B. Hintermann (eds.), *Emissions Trading as a Policy Instrument*, CESifo Seminar Series, MIT Press.

Heindl. P., P. Wood and F. Jotzo (2015). Combining international cap-and-trade with national carbon taxes, Ch. 6 in M. Gronwald and B. Hintermann (eds.), *Emissions Trading as a Policy Instrument*, CESifo Seminar Series, MIT Press.

Hepburn, C. (2006). Regulation by prices, quantities, or both: a review of instrument choice. *Oxford Review of Economic Policy* 22, 226-247.

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

Hoel, M. and T. Sterner (2007). Discounting and relative prices. *Climatic Change* 84: 265–280.

Jacoby, H.D. and A.D. Ellerman (2004). The safety valve and climate policy. *Energy Policy* 32, 481-491.

Kaplow. L. (1996). The optimal supply of public goods and the distortionary cost of taxation, *National Tax Journal* 49, 513-533.

Koch, N., S. Fuss, G. Grosjean, and O. Edenhofer (2014). Causes of the EU ETS price drop: recession, CDM, renewable policies or a bit of everything? New evidence. *Energy Policy* 73, 676-685.

Kollenberg, S. and L. Taschini (2016). Emissions trading systems with cap adjustments. *Journal of Environmental Economics and Management* 80, 20-36.

McKibbin, W.J. and P.J. Wilcoxen (1997). A better way to slow global climate change. Brookings Policy Brief No. 66, The Brookings Institution.

Murray, B.C., R.G. Newell, and W.A. Pizer (2009). Balancing costs and emissions certainty: an allowance reserve for cap-and-trade. *Review of Environmental Economics and Policy*, 1-20.

National Institute of Economic Research (2018). EU ETS, marknadsstabiliseringsreserven och effecter av annulleringar. Specialstudier, Konjunkturinstitutet, KI-nr: 2018:10.

Newell, R.G. and W.A. Pizer (2003). Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management* 45, 416-432.

Newell, R.G., W.A. Pizer, and J. Zhang (2005). Managing permit markets to stabilize prices. *Environmental and Resource Economics* 31, 133-157.

Nordhaus, W.D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America* 114 (7), 1518-1523.

Perino, G. and M. Willner (2016). Procrastinating reform: the impact of the Market Stability Reserve on the EU ETS. *Journal of Environmental Economics and Management* 80, 37-52.

Perino, G. and M. Willner (2017). EU-ETS Phase IV: allowance prices, design choices, and the Market Stability Reserve. *Climate Policy* 17, 936-946.

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

Salant, S. W. (2016). What ails the European Union's emissions trading system? *Journal of Environmental Economics and Management* 80, 6-19.

Sandbag (2016a). Getting in touch with reality – Rebasing the EU ETS Phase 4 cap. London and Brussels, June 2016.

Sandbag (2016b). Puncturing the waterbed myth. London and Brussels, October 2016.

Sandbag (2016c). Comparing options for addressing EU ETS oversupply. London and Brussels, December 2016.

Sinn, H.-W. (2008). Public policies against global warming: A supply-side approach. *International Tax and Public Finance* 15: 360–94.

Stern, N. (2007). *The Economics of Climate Change – The Stern Review*. Cambridge University Press.

Sterner, T. and U. M. Persson (2008). An even Sterner Review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy* 2, 61–76.

Phaneuf, D.J. and T. Requate (2017). *A Course in Environmental Economics - Theory, Policy, and Practice.* Cambridge University Press.

Nordhaus, W.D. (2007). To tax or not to tax: alternative approaches to slowing global warming. *Review of Environmental Economics and Policy* 1, 26-44.

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

Silbye, F. and P.B. Sørensen (2017). Subsidies to renewable energy and the European Emissions Trading System: is there really a waterbed effect? Working Paper, Danish Council on Climate Change, March 2017 (file:///C:/Users/kzj109/Downloads/working_paper_-_is_there_really_a_waterbed%20(3).pdf)

van den Bijgaart, I.M., R. Gerlagh, and M. Liski (2016). A simple formula for the social cost of carbon. *Journal of Environmental Economics and Management* 77, 75-94.

van der Ploeg, F. and C. Withagen (2012). Is there really a green paradox? *Journal of Environmental Economics and Management* 64 (3): 342–63.

Weitzman, M.L. (1974). Prices versus quantities. *Review of Economic Studies* 41, 477-491.

Weitzman, M.L. (1978). Optimal rewards for economic regulation. *American Economic Review* 68, 683-691.

APPENDIX A

The demand for emission allowances and the equilibrium allowance price

This appendix derives the formulas for the demand for emission allowances and the equilibrium allowance price reported in section 3. We will slightly generalize the analysis in that section by allowing for an abatement subsidy granted at the rate *s* per unit of CO_2 emission abated. The formula (1) for the present value of emissions-related net expenses then generalizes to

$$PV = \sum_{t=1}^{h} (1+r)^{-(t-1)} \left[p_t X_t + TAC_t - s_t \left(\bar{E}_t - E_t \right) \right]. \tag{A.1}$$

Minimizing this present value is equivalent to maximizing $-PV$. The maximization must respect the constraints (2) and (3) in section 3, including the inequality constraints $-S_t \leq 0$. Inserting (2) and the first equality in (3) into (A.1) and multiplying by minus one, we can write the Lagrangian for this non-linear programming problem as

$$L = -\sum_{t=1}^{h} (1+r)^{-(t-1)} \left[p_t \left(E_t + S_t - S_{t-1} \right) + \frac{1}{2b} \left(\bar{E}_t - E_t \right)^2 - s_t \left(\bar{E}_t - E_t \right) \right] + \sum_{t=1}^{h} \lambda_t S_t, \tag{A.2}$$

where the lambdas are the Kuhn-Tucker multipliers associated with the inequality constraints. The first-order conditions for maximization of (A.2) with respect to E_t and S_t are

$$\frac{\partial L}{\partial E_t} = 0 \quad \Rightarrow \quad \frac{1}{b} \left(\bar{E}_t - E_t \right) = p_t + s_t, \qquad t = 1, 2, ..., h. \tag{A.3}$$

$$\frac{\partial L}{\partial S_t} = 0 \quad \Rightarrow \quad - \ (1+r)^{-(t-1)} p_t + (1+r)^{-t} p_{t+1} + \lambda_t = 0, \qquad t = 1, 2, ..., h. \tag{A.4}$$

In addition, an optimal solution must satisfy the complementary slackness conditions

$$\lambda_t \geq 0, \qquad S_t \geq 0, \qquad \lambda_t S_t = 0, \qquad t = 1, 2, ..., h. \tag{A.5}$$

From (2) in section 3 we see that the expression on the left-hand side of (A.3) is the marginal abatement cost, defined as $MAC_t \equiv -dTAC_t / dE_t$. Hence (A.3) documents eq. (21) in section 6. Rearranging (A.3), we get

$$E_t = \bar{E}_t - b \left(p_t + s_t \right), \tag{A.6}$$

which boils down to eq. (4) in section 3 when $s_t = 0$. From (A.6) we see that national abatement subsidies (which could take the form of subsidies to renewable energy) are equivalent to a downward shift in our parameter $\bar{E}_t$, as stated in section 5.

From (A.5) we see that $\lambda_t = 0$ when $S_t > 0$. It then follows from (A.4) that

$$p_{t+1} = (1+r)\, p_t \quad \text{for} \quad S_t > 0, \tag{A.7}$$

which is identical to (5) in section 3. When $S_t = 0$ the complementary slackness conditions in (A.5) imply that $\lambda_t \geq 0$ in which case we see from (A.4) that

$$p_{t+1} = p_t (1+r) - \lambda_t \quad \Rightarrow \quad p_{t+1} \leq p_t (1+r) \quad \text{for} \quad S_t = 0, \tag{A.8}$$

as stated in (6) in section 3.

We can now derive the equilibrium allowance price in year 1. In year *T* when the allowance surplus vanishes, we have $S_T = 0$. Inserting this into eq. (7) in section 3, setting $t = T$, and rearranging, we find that equilibrium in the allowance market in year *T* implies

$$E_T^a = S_0 + Q_T^a - M_T^a,$$
$$E_T^a \equiv \sum_{t=1}^{T} E_t, \qquad Q_T^a \equiv \sum_{t=1}^{T} Q_t, \qquad M_T^a \equiv \sum_{t=1}^{T} \left(M_t^{IN} - M_t^{OUT} \right). \tag{A.9}$$

Throughout the period from year 1 until the end of year *T* when the cap on total accumulated emissions just becomes binding, the constraint $S_t \geq 0$ is not strictly binding, so during this span of years (including year *T*) we have $\lambda_t = 0$, implying from (A.7) and (A.8) that

$$p_{t+1} = (1+r)\, p_t \quad \text{for} \quad t = 1, 2, ..., T, \quad \Rightarrow$$
$$p_t = (1+r)^{t-1}\, p_1 \quad \text{for} \quad t = 1, 2, ..., T. \tag{A.10}$$

Using (A.6) and (A.10) and abstracting from subsidies so that $s_t = 0$, we can write the term E_T^a defined in (A.9) as

$$E_T^a = \bar{E}_T^a - bp_1 \left[1 + (1+r) + (1+r)^2 + ... + (1+r)^{T-1} \right]$$
$$= \bar{E}_T^a - \frac{bp_1}{r} \left[(1+r)^T - 1 \right], \qquad \bar{E}_T^a \equiv \sum_{t=1}^{T} \bar{E}_t. \tag{A.11}$$

Inserting (A.11) in (A.9) and solving for p_1, we obtain the expression for the equilibrium allowance price stated in (12) in section 3.   Q.E.D.

Appendix B

Measuring the cost-effectiveness of national climate policies

This appendix explains the derivation of the cost-effectiveness formulas (18) and (19) in section 3. The starting point is the social welfare function (17) which we repeat here for convenience:

$$SW_t = CS_t + PS_t + p_t Q_t^d - \left(c_t^R - q_t\right) R_t, \tag{B.1}$$

where we recall that CS is the consumer surplus from household energy consumption, PS is the producer surplus from energy consumption in the business sector, Q^d is the quantity of emission allowances which the government is entitled to issue under the rules of the ETS, q is the price of energy, R is the quantity of domestic renewable energy production, and c^R is the cost of producing one unit of renewable energy. Since R and Q^d are measured in comparable units, a unit rise in R causes emissions to fall by one ton at any given allowance price p. The magnitude $c^R - q$ is the subsidy granted per unit of renewable energy produced, and the government controls the quantity R of renewable energy by determining how many units of R to subsidize.

We assume that the fossil-based and renewables-based energy services (e.g. electricity and heat) are perfect substitutes and therefore sell at the common price q. From standard welfare economics we know that the effect of a unit rise in the price of energy on the consumer and producer surplus will be

$$\frac{\partial CS_t}{\partial q_t} = -E_t^h, \qquad \frac{\partial PS_t}{\partial q_t} = -E_t^f, \tag{B.2}$$

where E^h is initial household energy consumption and E^f is the initial energy consumption by firms. We may choose units of measurement such that the amount of fossil consumption which generates one ton of CO_2 emissions also produces one unit of the final energy service. Recall that one unit of renewables-based energy production equals the amount of fossil-based energy production which generates an emission of one ton of CO_2, and let F^d denote the consumption of fossil fuels in the domestic ETS sector which is also equal to total CO_2 emissions from the sector. With E^h, E^f, F^d and R being measured in identical units, and since total energy consumption must be either fossil-based or renewables-based, we thus have

$$E_t^h + E_t^f = F_t^d + R_t . \tag{B.3}$$

In a long-run competitive equilibrium where firms earn zero profits, the equilibrium price of energy must equal the unit cost of fossil-based energy production, so a change in the allowance price will be fully passed through to energy consumers. i.e., $dq_t / dp_t = 1$. Combining this result with (B.2) and (B.3), we can use (B.1) to derive the welfare gain from of a unit increase in the quantity of emission allowances in year 1 which is also the welfare cost of cutting the supply of allowances by one unit in that year:

$$SC_1^Q = \frac{dSW_1}{dQ_1^d} = p_1 + \frac{dp_1}{dQ_1^d}\left(Q_1^d - F_1^d\right), \tag{B.4}$$

$$SC_t^Q = \frac{dSW_t}{dQ_1^d} = \frac{dq_t}{dQ_1^d}\left(Q_t^d - F_t^d\right), \qquad 2 \le t \le H. \tag{B.5}$$

The term $p_1 + \left(dp_1 / dQ_1^d\right)Q_1^d$ on the right-hand side of (B.4) is the loss of public revenue in year 1 when the government sells one less unit of allowances in that year. Using (B.3), we may write the term $-\left(dp_1 / dQ_1^d\right)F_1^d$ on the RHS of (B.4) as $-\left(dp_1 / dQ_1^d\right)\left(E_1^h + E_1^f - R_1\right)$. The term $-\left(dp_1 / dQ_1^d\right)\left(E_1^h + E_1^f\right)$ is the welfare loss for energy consumers resulting from the higher price of energy, while the term $-\left(dp_1 / dQ_1^d\right)\left(-R_1\right)$ captures the gain in public net revenue when the higher market price of energy reduces the necessary subsidy to renewable energy. This revenue gain can be transferred to consumers to compensate them for part of their welfare loss. In year *t* the change in the allowance price induced by the change in Q_1^d will be dp_t / dQ_1^d. A higher allowance price in year t will increase the government's net revenue by the amount $\left(dp_t / dQ_1^d\right)\left(Q_t^d + R_t\right)$, where $\left(dp_t / dQ_1^d\right)Q_t^d$ is the higher revenue from the auctioning of allowances and $\left(dp_t / dQ_1^d\right)R_t$ is the fall in expenditure on the necessary subsidies to renewables. At the same time the higher energy price will reduce the welfare of energy consumers by the amount $\left(dq_t / dQ_1^d\right)\left(E_t^h + E_t^f\right)$. Noting from (B.3) that $R_t - \left(E_t^h + E_t^f\right) = -F_t^d$, we see that the net social gain from a higher allowance price in year t will be $\left(dp_t / dQ_1^d\right)\left[\left(Q_t^d + R_t\right) - \left(E_t^h + E_t^f\right)\right] = \left(dp_t / dQ_1^d\right)\left(Q_t^d - F_t^d\right)$. This is the magnitude appearing in (B.5) which shows that the net effect on social welfare is negative (positive) if the country is a net importer (exporter) of allowances.

Consider next the social cost of increasing the production of renewable energy by one unit in year 1. A unit increase in R will cause a corresponding downward shift in the emissions function (4), i.e., $d\bar{E}_1 = -dR_1$, and from (12) it follows that $dp_1 / d\bar{E}_1 = -dp_1 / dQ_1^d$ since Q_1^d is part of the aggregate Q_T^a. Using these results along with (B.1) through (B.3), and recalling that $dq_t / dp_t = 1$, we find that the social cost of expanding renewable energy production by one unit in year 1 (equal to $-dSW_t / dR_1$) is

$$SC_1^R = c_1^R - q_1 - \frac{dp_1}{dQ_1^d}\left(Q_1^d - F_1^d\right), \tag{B.6}$$

$$SC_t^R = -\frac{dp_t}{dQ_1^d}\left(Q_t^d - F_t^d\right), \qquad 2 \le t \le H. \tag{B.7}$$

The term $c_1^R - q_1$ on the RHS of (B.6) is the subsidy needed to increase the amount of renewable energy production in year 1 by one unit. Since the subsidy equals the difference between the marginal cost of renewable energy and the marginal utility deriving from it (reflected in its price), it represents a social cost of expanding renewable energy production. The term $-\left(dp_1 / dQ_1^d\right)Q_1^d$ in (B.6) is the government's loss of revenue as the larger supply of renewables drives down the price of allowances auctioned by the state. On the other hand, since $dq_t / dp_t = 1$, the cheaper energy implied by the lower price of allowances increases private sector welfare by the amount $-\left(dp_1 / dQ_1^d\right)\left(E_1^h + E_1^f\right)$, but at the same time it increases the need for subsidies to renewables by the amount $-\left(dq_1 / dQ_1^d\right)R_1$. Recalling that $E_1^h + E_1^f - R_1 = F_1^d$, the net effect on social welfare is $-\left(dq_1 / dQ_1^d\right)F_1^d$, as stated in the last term on the RHS of (B.6). In the subsequent years, the fall in the allowance price caused by the rise in R_1 generates a net social welfare loss equal to the expression on the RHS of (B.7). This loss is positive in so far as the amount of allowances sold by the government exceeds the total emissions by the domestic private sector. i.e., in so far as the country is a net exporter of allowances, since the government will then lose more from the lower allowance price than the private sector will gain from it.

If the policy horizon does not extend beyond the year when the allowance surplus vanishes $(H \leq T)$, we know from (A.10) in Appendix A that $p_t = (1+r)^{t-1} p_1$. Inserting this along with (B.4) and (B.5) into (15) in section 3, we obtain the result stated in (18) in section 3. The expression (19) for the social cost of reducing the present value of emissions by one unit via expansion of renewable energy supply is found by inserting (B.6) and (B.7) in (16) and using $p_t = (1+r)^{t-1} p_1$. Q.E.D.

Appendix C

A simple political economy model of the ETS

This appendix documents the results from our political economy model of the ETS reported in section 6. The model assumes that EU policy makers adjust the aggregate supply of emission allowances as if they were trying to minimize a social loss function of the simple quadratic form

$$SL = \frac{1}{2}V_1^2 + \frac{\alpha}{2}p_1^2, \qquad \alpha > 0, \tag{C.1}$$

where V_1 is the present value of CO_2 emissions, and α is a parameter reflecting the intensity of political preferences for low allowance prices relative to the preference for low emissions. The motivation for the specification (C.1) was given in section 6.

We will consider the effects of the two domestic policy instruments Q_1^d and R_1 introduced in Appendix B. Recalling that the renewable energy supply R_1 causes a corresponding downward shift in the emissions function (4) so that emissions in year 1 may be written as $E_1 = \bar{E}_1 - R_1 - bp_1$, we can restate the equilibrium condition (12) for the allowance market as

$$p_1 = \frac{r\left[\bar{E}_T^a - \left(R_1 + X\right)\right]}{b\left[\left(1+r\right)^T - 1\right]}, \qquad X \equiv S_0 + Q_T^a - M_T^a, \tag{C.2}$$

where X is the cumulative EU-wide supply of emission allowances available up until T. Equation (C.2) defines p_1 as an implicit function of $R_1 + X$, i.e.,

$$p_1 = p\left(R_1 + X\right), \qquad p' = -\beta, \qquad \beta \equiv \frac{r}{b\left[\left(1+r\right)^T - 1\right]} > 0.. \tag{C.3}$$

Recall from section 6 that our specification (C.1) implicitly assumes that the policy horizon H does not extend beyond the year T when the allowance surplus vanishes (according to our simulations, this will not happen until some time in the mid-2050s). It then follows from (5) that $p_{t+1} = \left(1+r\right)p_t$ for all $t \leq H$. Using this along with (4), (C.3), and our definition of CER_H^Q stated in (13), we may write the present value of emissions over the policy horizon H as

$$V_1 = g\left(R_1 + X\right) - R_1, \qquad g\left(R_1 + X\right) \equiv \sum_{t=1}^{H} \left\{ \frac{\overbrace{\bar{E}_t - b\left(1+r\right)^{t-1} p\left(R_1 + X\right)}^{=E_t}}{\left(1+\rho\right)^{t-1}} \right\},$$

$$g' = b\beta \sum_{t=1}^{H} \left(\frac{1+r}{1+\rho} \right)^{t-1} = \sum_{t=1}^{H} \frac{dE_t / dQ_1^d}{\left(1+\rho\right)^{t-1}} \equiv CER_H^Q > 0, \tag{C.4}$$

where the final result in the bottom line of (C.4) follows from the fact that Q_1^d enters additively in the definition of X with a coefficient of one ($dX / dQ_1^d = 1$). With the notation in (C.3) and (C.4) the social loss function (C.1) can be written in the form

$$SL = \frac{1}{2}\left[g\left(R_1 + X\right) - R_1 \right]^2 + \frac{\alpha}{2}\left[p\left(R_1 + X\right) \right]^2. \tag{C.5}$$

We imagine that EU policy makers choose X with the purpose of minimizing the social loss in (C.5), taking the renewables-policies of individual member states as given. Given the expressions for the derivatives p' and g' stated in (C.3) and (C.4), the first-order condition for the solution to this problem is

$$\partial SL / \partial X = 0 \quad \Rightarrow$$

$$CER_H^Q \left[g\left(R_1 + X\right) - R_1 \right] - \alpha\beta p\left(R_1 + X\right) = 0, \tag{C.6}$$

and the second-order condition is $\partial^2 SL / \left(\partial X\right)^2 = \left(CER_H^Q\right)^2 + \alpha\beta^2 > 0$ which is seen to be satisfied. The first term on the left-hand side of (C.6) is the marginal benefit from lower emissions, and the second term is the marginal benefit from a lower allowance price. In the optimum, these two marginal benefits must balance each other.

Suppose now that an individual EU member state, say Denmark, wants to pursue a more ambitious climate policy by annulling some of the allowances it is entitled to issue under the rules of the ETS, as could be the case if Danish policy makers assign a higher value to emission reductions than the average EU policy maker. As a result of such a policy action (a cut in Q_1^d) in Denmark, the magnitude of X will ceteris paribus fall below the level satisfying (C.6), and the allowance price will be driven above the level implied by (C.6). But if the political preferences of

Denmark are already reflected in the value of α and the preferences of the other member states are unchanged, EU policy makers will want to offset the annulment of allowances undertaken by Denmark by increasing the allocation of allowances to other member states by a corresponding amount to ensure that the optimum condition (C.6) is still satisfied. In practice, this could be implemented by an appropriate design of a market stability reserve. In other words, the effort of a single member state to reduce the aggregate supply of allowances and drive up the allowance price will be completely ineffective once we allow for endogenous adjustment of allowance supply at the EU level.

But suppose instead that the ambitious member state decides to expand the supply of renewable energy so that R_1 increases. According to (C.3), (C.4) and (C.6) this will trigger the following subsequent adjustment of aggregate allowance supply at the EU level:

$$\frac{\partial X}{\partial R_1} = -1 + \frac{CER_H^Q}{\left(CER_H^Q\right)^2 + \alpha\beta^2} \quad . \tag{C.7}$$

We see from (C.7) that the expansion of renewable energy supply will not be fully offset by a corresponding reduction in allowance supply at the EU level. To calculate the effect on the present value of emissions and on the allowance price, we note from (C.3), (C.4) and (C.7) that

$$\frac{dV_1}{dR_1} = CER_H^Q - 1 + CER_H^Q \frac{\partial X}{\partial R_1} = -\frac{\alpha\beta^2}{\left(CER_H^Q\right)^2 + \alpha\beta^2} < 0 \,, \tag{C.8}$$

$$\frac{dp_1}{dR_1} = -\beta\left(1 + \frac{\partial X}{\partial R_1}\right) = -\frac{\beta CER_H^Q}{\left(CER_H^Q\right)^2 + \alpha\beta^2} < 0 \,. \tag{C.9}$$

In contrast to an annulment of allowances, we see from (C.8) that part of an expansion of renewable energy supply by an individual member state will indeed translate into a fall in the present value of emissions. The intuition for this result was given in section 6. Q.E.D.