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SUBSIDIES TO RENEWABLE ENERGY
AND THE EUROPEAN EMISSIONS TRADING SYSTEM:
IS THERE REALLY A WATERBED EFFECT?

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Abstract: We set up a model of the European Emissions Trading System with forward-looking market behaviour. The model is calibrated to market data for 2017 and incorporates current and future plans 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, and there is a risk that it will be permanent, despite the establishment of the MSR. Hence a limited annulment of emission allowances at the individual EU Member State level, expected to be part of EU climate policy until 2030, will not have any substantial impact on CO_2-emissions for decades to come. In contrast, subsidies to renewable energy are likely to be a far more cost-effective way of reducing emissions if policy makers cannot agree on a comprehensive reform of the ETS. Paradoxically, we find that this conclusion is strengthened by the introduction of the MSR.

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

1. The issue: Does the European cap-and-trade system make subsidies to renewable energy ineffective?

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. Are these subsidies largely ineffective? Many economists and policy makers believe the answer is "Yes". They point out that most energy production in the EU is covered by the European Emissions Trading System (ETS) which requires energy producers to submit CO_2 emission allowances corresponding to their emissions. If the total supply of allowances is a binding cap on total emissions, subsidies to fossil-free sources of energy will fail to reduce aggregate emissions, since the resulting fall in demand for allowances will induce a fall in their price until total emissions are again equal to the fixed supply of allowances. Hence subsidies to renewables have no beneficial effect on the climate: while they may reduce emissions from some sources, they will just increase emissions from other sources by an equivalent amount, just as squeezing a waterbed in one place immediately leads to it bulging out in another – or so the argument goes.

The present paper argues that this waterbed analogy may be seriously misleading, given the current state of the market for ETS allowances. As pointed out by Sandbag (2016a) and many others, the total supply of allowances available to the market greatly exceeds total emissions from the ETS sector so the system does not currently impose a binding cap on emissions. In reaction, EU policy makers have decided to establish a so-called Market Stability Reserve (MSR) to which some of the surplus of allowances will be transferred from 2019 and onwards. But as we will show, this limited reform of the ETS may well fail to eliminate the surplus of allowances on this side of 2050. In these circumstances subsidies to renewable energy within the ETS sector will reduce total CO_2 emissions for quite a long time and will therefore slow down climate change, even if they will not reduce the stock of carbon in the atmosphere in the very long run if the surplus of allowances is ultimately

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eliminated. Moreover, our analysis points to a significant risk that the surplus will never disappear in which case subsidies to renewables will permanently curb emissions. Our analysis supports that of Sandbag (2016a,b); a think tank which has repeatedly warned that the ETS is heading towards a structural surplus of allowances that threatens to reduce the system to a mere CO_2 accounting scheme without any real effect on the climate.

Our analysis is based on a dynamic partial equilibrium model of the market for ETS allowances which accounts for the existence of a temporary allowance surplus that may vanish in the long run. The model incorporates the dynamics of the planned Market Stability Reserve and enables us to forecast the evolution of CO_2-allowances and the allowance surplus under alternative policy scenarios. We use the model to compare the dynamic effects on CO_2 emissions of an increase in renewable energy supply to the effects of a withdrawal of allowances from the market by an individual EU member state. This provides an illustration of the surprising and far-reaching consequences of the Market Stability Reserve. Second, we present a simple methodology for estimating the cost-effectiveness of these two alternative climate policies over various time horizons, using inputs from our model. Our analysis suggests that, from the perspective of an individual EU member state with a policy horizon stretching to 2030 or even to 2050 and beyond, subsidies to renewable energy may well be a more cost-effective way of reducing CO_2 emissions than withdrawal of ETS allowances. Third, we offer a simple political economy theory of the supply of emissions allowances which provides further support for our hypothesis that subsidies to renewable energy may be a more effective climate policy than annulment of allowances from the perspective of the individual EU member country.

Many authors - 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 pointed out that the overlapping regulation implied by the combination of national subsidies to renewables and the EU-wide cap-and-trade system for the ETS sector increases the cost of meeting EU climate policy targets. The reasons are that the subsidies may prevent the equalization of marginal social production costs across different energy technologies and that different national subsidy rates hinder the establishment of a common carbon price across Member States, thereby preventing a cross-country equalization of marginal abatement costs. We fully agree that a common carbon price in the EU at an appropriate level would indeed be desirable, but many member states see the current market price of ETS allowances as being too low to drive the transition to renewable energy at a satisfactory pace. Rather than granting subsidies to renewables which only tend to reduce the price of allowances even further, an obvious remedy to this problem would be a significant reduction of the aggregate supply of allowances. Unfortunately it has proved very difficult to reach political agreement on such a reform at the EU level. In this situation an important issue for the more ambitious member states is whether the climate is better served by subsidies to renewables rather than an annulment of allowances at the national level. The present paper offers a methodology for answering this question.

In an interesting recent paper Lecuyer and Quirion (2013) have presented a rationale for subsidizing renewables in the European ETS sector, given the uncertainty about the future stringency of the

ETS cap on total emissions. Lecuyer and Quirion show that subsidies to renewable electricity production may be part of a socially optimal climate policy even though emissions from electricity production are covered by a cap-and-trade system like the ETS. The reason is that the future cap on emissions may fail to bind if the demand for allowances drops due to a negative shock to electricity demand or due to a positive shock to fossil fuel prices. In such a situation where the price of allowances collapses to a level far below the marginal social cost of emissions, the subsidies to renewables will guarantee that some abatement of emissions will nevertheless take place.

The present paper may be seen as a complement to that by Lecuyer and Quirion (op.cit.). In their static model subsidies to renewables are completely ineffective when the cap on total emissions is binding. In our dynamic model with a surplus of allowances in the short and medium term, the subsidies can have beneficial effects by postponing emissions even if the cap becomes binding some time in the future. Our model allows us to calculate the effective cut in CO_2 emissions in some given future year attained through an increase in renewable energy production in the current year.

Our analysis is heavily inspired by the Sandbag (2016b) study of the potential waterbed effect associated with various policy measures that would reduce the demand for ETS allowances.[3] We go beyond that study by undertaking a more systematic analysis of two particular climate policies (annulment of allowances vs. subsidies to renewables), by presenting a more detailed analysis of the effects of the ETS Market Stability Reserve, by analyzing the cost-effectiveness of the two alternative climate policies considered, and by offering a formal political economy analysis of the determination of the supply of emission allowances.

The rest of the paper is structured as follows. Section 2 briefly describes the history and current status of the EU Emissions Trading System. Against this background, section 3 sets up a model of the market for ETS allowances and CO_2 emissions from the ETS sector and uses the model to derive formulas for the dynamic effects on emissions of an annulment of allowances and an increase in renewable energy production. Section 4 discusses the choice of the discount rate applicable to future emissions changes, and Section 5 calibrates the model to data for the ETS. In Section 6 we present forecasts for the evolution of emissions and the surplus of ETS allowances under alternative climate policies, and Section 7 shows how the model may be used to estimate the cost-effectiveness of alternative policies to curb emissions. Section 8 discusses the effects of national climate policies in a setting where the total supply of emission allowances is determined endogenously by political economy considerations at the EU level. The main conclusions of the paper are summarized in section 9.

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[3] The Sandbag study presents simulations based on a model of the ETS which appears to have several features in common with the model developed by the Danish Council on Climate Change (DCCC) presented here, but since the mathematical specification of the Sandbag model is not publicly available, we cannot describe exactly how it deviates from the DCCC model.

2. The European Union Emissions Trading System[4]

The ETS covers about 45 percent of CO_2 emissions in the EU[5]. The system applies to CO_2 emissions and equivalent amounts of nitrous oxide and perfluorocarbons from installations in energy-intensive industrial sectors[6]. By April 30 of each year registered firms in the ETS sector must surrender emission permits corresponding to their emissions in the previous calendar year. The permits 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.

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 2005-2015. 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 Phase II[7]. 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. The cumulative allowance surplus has fallen slightly in 2014 and 2015 as the newly issued allowances and offsets fell short of verified emissions in those years. However, the allowance surplus still exceeds total annual emissions from the ETS sector by a considerable margin.

In 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, it is expected that the annual linear reduction of the cap will be 2.2 percent.

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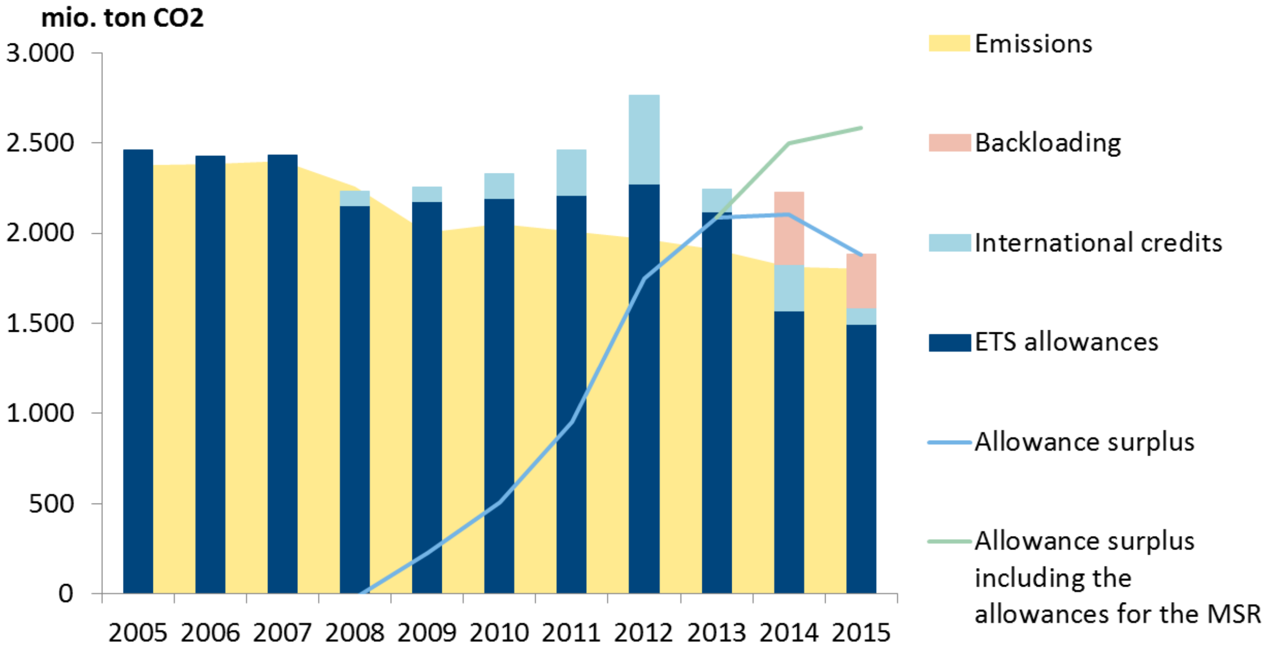
[4] This section draws on Gronwald and Hintermann (2015) who provide a more detailed account of the history of the ETS.

[5] Norway, Iceland and Liechtenstein have linked their national permit systems to the ETS, so the system involves a total of 31 countries.

[6] Since 2012 emissions from aviation have been included as well, but this sector has a separate emissions cap.

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

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



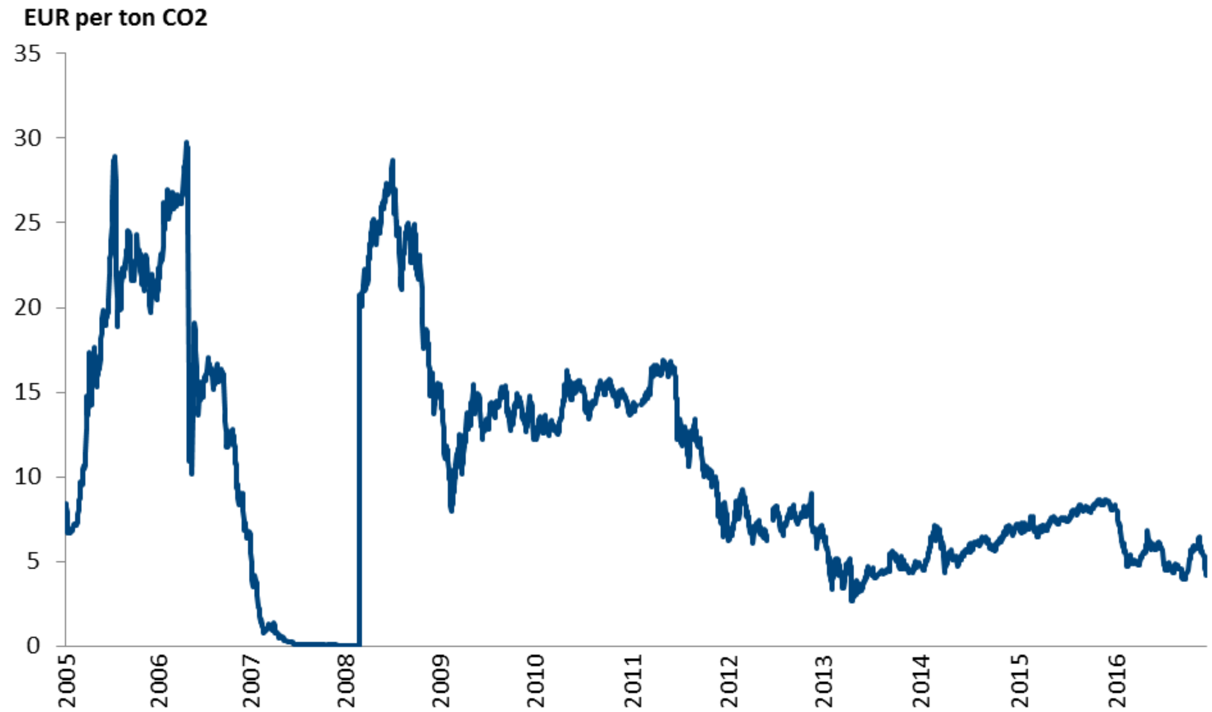
Note: "Backloading" implied that 400 Mt and 300 Mt of allowances were held back from the market in 2014 and 2015, respectively. The backloaded allowances will be placed in the MSR from 2019. They are included in the allowances surplus shown by the green graph in the figure.

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.*

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.

The fact that the price of allowances remains positive despite the current allowance surplus must reflect that allowances can be banked and that market participants believe there is a positive probability that the surplus will someday disappear. However, the low current price suggests that the market expects the price to remain low for a long time or that there is a significant risk that the system will break down due to a permanent allowance surplus.

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



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].

In reaction to the large surplus of allowances, EU policy makers have recently decided to introduce a so-called Market Stability Reserve (MSR) from 2019. Whenever the allowance surplus exceeds 833 million tons of CO_2, 12 percent of the surplus will be withdrawn from the market and kept in the reserve. When the surplus falls below 400 million tons of CO_2, the allowances in the MSR will be released back to the market at an annual rate of 100 million tons per year. Thus the MSR does not permanently reduce the total supply of allowances, and so far the plan to introduce it has failed to induce a significant increase in the allowance price.

With these market facts in mind, we will now set up a simple partial equilibrium model of the market for ETS allowances to analyze the effects of alternative climate policies.

3. A simple model of the ETS

The model determines time paths for the evolution of the allowance price (q) and CO_2 emissions, given exogenous time paths for the price of fossil fuel (f) and the annual issue of new allowances (Q). The annual CO_2 emissions are proportional to the annual consumption of fossil fuels (F) and we use the normalization that one unit of fossil fuel consumption generates one ton of CO2 emission. The total cost of consuming one unit of fossil fuel is then equal to $f+q$, and the demand for fossil fuels in the ETS sector in year t is assumed to be given by

$$F_t = \max\left\{0, a_t - b\left(f_t + q_t\right)\right\}, \qquad b > 0. \tag{1}$$

This specification allows for the possibility that fossil fuel demand collapses to zero if the exogenous demand shift parameter a_t falls by a large amount, say, because alternative sources of energy become sufficiently cheap. However, in general we see from (1) that fossil fuel demand is taken to be a linear function of the cost of fuel, with the shift parameter a_t capturing all changes in demand other than those stemming from changes in fuel costs. Rather than assuming a constant absolute price sensitivity b, we could have assumed a constant price elasticity, but in that case the model would not be able to simulate a scenario where the allowance price collapses to zero due to a permanent allowance surplus, since a constant price elasticity would generate an infinitely high demand for allowances when the allowance price tends to zero. This is the motivation for our choice of a linear demand curve.

The annual CO2 emission is F, 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 Market Stability Reserve in the year considered, or a quantity M^{IN} of allowances may be transferred to the MSR. If the cumulative allowance surplus at the end of year zero is S_0, the cumulative surplus at the end of year t will therefore be

$$S_t = S_0 + \sum_{i=1}^{t}\left(Q_i - F_i - M_i^{IN} + M_i^{OUT}\right). \tag{2}$$

The rules for the MSR imply that 12 percent of the cumulative allowance surplus recorded two years earlier must be transferred to the reserve if the cumulative surplus in the current year exceeds 833 million tons of CO2. Otherwise the transfer to the fund is zero. Hence

$$M_t^{IN} = \begin{cases} 0.12 \cdot S_{t-2} & \text{if } S_t > 833 \\ 0 & \text{if } S_t \le 833 \end{cases} \tag{3}$$

The rules for the MSR also stipulate that allowances amounting to 100 million tons of CO2 (or the entire remaining reserve if this is smaller than 100 million tons) must be released from the reserve whenever the cumulative allowance surplus falls short of 400 million tons, whereas no release can take place at a cumulative surplus below this level. If the reserve at the end of year $t-1$ is M_{t-1}, we therefore have

$$M_t^{OUT} = \begin{cases} \min\left\{100, M_{t-1}\right\} & \text{if } S_t < 400 \\ 0 & \text{if } S_t \ge 400 \end{cases} \tag{4}$$

With a reserve of M_0 at the end of year zero, the cumulative reserve in the MSR at the end of year t is

$$M_t = M_0 + \sum_{i=1}^{t} \left(M_i^{IN} - M_i^{OUT} \right). \tag{5}$$

Saving allowances for the future is worthwhile only if the expected return to such saving matches the expected return r obtainable on other financial assets with similar risk characteristics. The expected return to investment in allowances is the expected increase in their price. When there is a positive allowance surplus, a rational expectations equilibrium in the market for allowances where investors obtain their required return and actual and expected prices coincide therefore requires that

$$q_t = \left(1 + r_t\right) q_{t-1} \quad \text{for} \quad S_{t-1} > 0. \tag{6}$$

If the allowance surplus is zero so that the cap on emissions is binding, 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 expected return to saving in alternative assets – otherwise it would pay to save some allowances for the future in which case the emissions cap would not be binding. Thus we have

$$q_t \leq \left(1 + r_t\right) q_{t-1} \quad \text{for} \quad S_{t-1} = 0. \tag{7}$$

If the allowance surplus is expected to persist forever so that allowances are in permanent excess supply, rational investors will expect all future allowance prices to be zero, i.e.,

$$q_t = 0 \quad \text{if} \quad S_\tau > 0 \quad \text{for all} \quad \tau \geq t. \tag{8}$$

Finally, an economically meaningful equilibrium must satisfy the non-negativity constraints

$$S_t \geq 0 \quad \text{and} \quad q_t \geq 0 \quad \text{for all } t. \tag{9}$$

For given values of the predetermined variables S_0 and M_0 and for given time paths of the exogenous variables a_t, f_t, Q_t and r_t, the model above determines the time paths of q_t, F_t, Z_t, W_t, M_t and S_t from year 1 and onwards.

Before calibrating and simulating the model it will be useful to derive a few analytical results. Reflecting the current market situation in the ETS, we assume that the system starts out with a positive allowance surplus S_0 but that the surplus disappears from some future year $T \geq 1$ and onwards (in our simulations we will include the special case where $T \to \infty$, i.e., where the surplus never disappears). For simplicity we will assume that the required return on investment in emission allowances is constant at the level r. From (6) it then follows that the allowance price in year t is

$$q_t = \left(1 + r\right)^{t-1} q_1 \quad \text{for} \quad t = 1, 2, ..., T. \tag{10}$$

We can now derive the initial equilibrium allowance price q_1, assuming that market participants correctly anticipate that the allowance surplus will disappear by the end of year T. Setting $S_T = 0$ in (6) and inserting (1), (5) and (10) in the resulting equation, we get

$$\overbrace{\sum_{t=1}^{T}\left\{a_t - b\left[f_t + (1+r)^{t-1} q_1\right]\right\}}^{\substack{\text{Cumulative demand for}\\ \text{emission allowances}\\ \text{from year 1 to year } T}} = S_0 + \overbrace{M_0 - M_T + \sum_{t=1}^{T} Q_t}^{\substack{\text{Cumulative allocation of}\\ \text{emission allowances to the}\\ \text{market from year 1 to year } T}} \quad . \tag{11}$$

Now consider a unit change in Q_1 and abstract for the moment from its subsequent impact on the Market Stability Reserve, M_T.[8] According to (11) the isolated effect of a change in Q_1 on the allowance price in year 1 will be

$$\frac{dq_1}{dQ_1} = -\frac{1}{b\left[1+(1+r)+(1+r)^2+\ldots+(1+r)^{T-1}\right]} = -\frac{r}{b\left[(1+r)^T - 1\right]}. \tag{12}$$

Even though the annual emissions cap does not become binding until year T, we see from (12) that the allowance price starts to rise already in year 1 as market participants anticipate a tighter emissions cap from year T onwards. Equation (10) implies that the effect of the change in Q_1 on the allowance price in year t is $dq_t / dQ_1 = (1+r)^{t-1}(dq_1/dQ_1)$, and from (1) it follows that $dF_t / dQ_1 = -b(dq_t / dQ_1)$ when $F_t > 0$. The changes in emissions occurring in different future years do not necessarily have the same present social value per unit, so 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 (the next section discusses the determinants of ρ and its likely magnitude). 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,

$$CER_H^Q \equiv \sum_{t=1}^{H}\frac{dF_t/dQ_1}{(1+\rho)^{t-1}} = \sum_{t=1}^{H}\frac{-b(dq_t/dQ_1)}{(1+\rho)^{t-1}} = -b\left(\frac{dq_1}{dQ_1}\right)\sum_{t=1}^{H}\left(\frac{1+r}{1+\rho}\right)^{t-1} \Rightarrow$$

$$CER_H^Q = \frac{r}{\tilde{r}}\left[\frac{(1+\tilde{r})^H - 1}{(1+r)^T - 1}\right], \qquad 1+\tilde{r} \equiv \frac{1+r}{1+\rho}, \qquad \rho \geq 0, \qquad 1 \leq H \leq T, \tag{13}$$

where we have used the expression for dq_1/dQ_1 given in (12). We will refer to the expression in (13) as the *Coefficient of Emission Reduction* (*CER*). Note from (13) that the *CER* does not only depend on the policy horizon H, but also on the year T in which the allowance surplus is expected

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[8] In the sections below we will account for the endogenous dependence of M_T on Q_1 implied by (3) through (5), but at the present stage it will be helpful to consider the effect of an isolated change in Q_1 to get a feel for the mechanisms at play in the model.

to vanish. In the special case of $\rho = 0$ where policy makers do not care about the timing of CO_2 emissions, it follows from (13) that $\tilde{r} = r$ so that

$$CER_H^Q = \frac{(1+r)^H - 1}{(1+r)^T - 1} \qquad \text{for } \rho = 0. \tag{14}$$

The numerator in (14) is the total relative increase in the allowance price from year 1 to year H, and the denominator is the total relative increase in the allowance price from year 1 to year T. With a linear schedule for fossil fuel demand, the cumulative reduction in CO_2 emissions over some period will be proportional to the rise in the allowance price over that period. Hence the cumulative emissions reductions from year 1 to year H ($\le T$) is proportional to the numerator in (14), and the cumulative emissions reduction from year 1 to year T is proportional to the denominator. In year T when the emissions cap becomes binding, the cumulative reduction of emissions will have to catch up with the initial reduction in the supply of allowances. Accordingly, we see from (14) that when the policy horizon coincides with the year when the allowance surplus disappears ($H = T$), (and when we abstract from the Market Stability Reserve, as we have done here), the *CER* is equal to 1. From then on there will be no further effect on emissions.

Equation (14) determines the *CER* when policy makers do not care whether a change in emissions occurs now or later. However, for the reasons mentioned above the social discount rate ρ in (13) will generally be positive. When the market for emissions allowances starts out with a surplus (i.e., when $T > 1$), it follows from (13) that the *CER* will always be smaller than 1 even for $H = T$.

Equation (13) summarizes the dynamic effects on emissions of a unit change in the supply of allowances in year 1. Going back to equation (11), we see that the effect of a one unit *increase* in Q_1 on the allowance price in year 1 is the same as the effect of a one unit *decrease* in the demand shift parameter a_1 which may come about through a subsidy to renewable energy that reduces the demand for fossil fuel. At any given fuel cost, the effect of a one unit drop in a_1 is to lower cumulative emissions by one unit,[9] but in addition it will have the same effect on emissions as a unit increase in the allowance supply by lowering the price of allowances. Hence the total *reduction* of the discounted cumulative emissions from year 1 through year H induced by a one unit fall in a_1 will be

$$CER_H^R = 1 - CER_H^Q, \qquad 1 \le H \le T. \tag{15}$$

Equation (15) 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. With a positive social discount rate applied to CO_2 emissions, CER_H^Q will

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[9] We assume here that the drop in *a* occurs only in year 1 to ensure comparability with the experiment of reducing Q_1 by one unit.

remain below 1 so that CER_H^Q will remain positive for all H, implying that subsidies to renewables energy will have some beneficial effect on discounted emissions even in the long run where the emissions cap is assumed to become binding.

4. The discount rate on CO2 emissions

When evaluating the effect of a change in the current allowance price 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 discount rate on goods is given by the standard Ramsey formula $r = \theta + \varepsilon g$, where 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

$$\frac{1}{1+\rho} = \frac{1+g^d}{1+r} = \frac{1+g^d}{1+\theta+\varepsilon g}, \tag{16}$$

where g^d is the rate of increase of the social cost of carbon (SCC). 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. (16) would imply that $\rho \approx \theta - n$. According to the latest forecast by the United Nations from 2015, 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 $\rho \approx \theta - n$ 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 parameter r averages $4\frac{1}{4}$ percent per year in his model simulation. According to (16) 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 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 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 implied by (16).

5. Calibrating the model

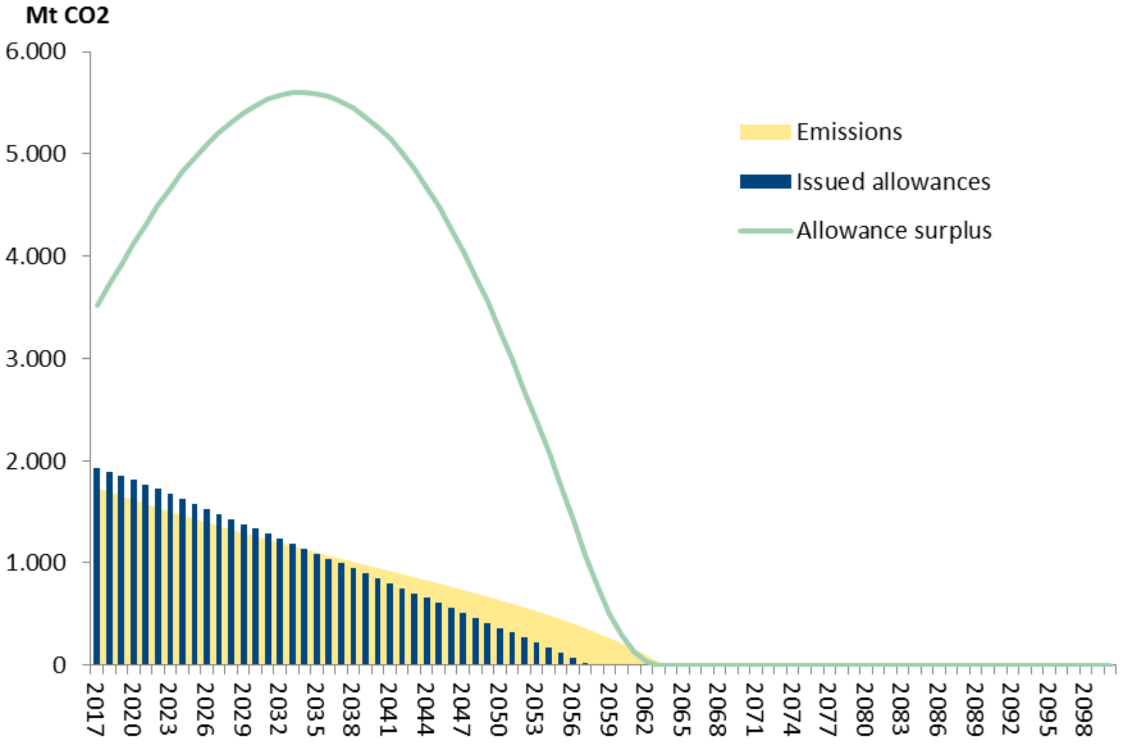
Since the fossil fuel price f_t is exogenous in our model, we can treat $a_t - bf_t$ as an exogenous composite demand shift term in the demand schedule for fossil fuel. To simulate our model of the ETS, given the initial allowance surplus S_0, we need to assign values to the required return on allowances (r) and the price sensitivity of fossil fuel demand (b) and to specify the exogenous time paths for the demand shift term $a_t - bf_t$ and the annual allocation of allowances Q_t. The model will then determine a time path for the evolution of the allowance price and CO_2 emissions as well as the number of years before the allowance surplus disappears, accounting for the endogenous dynamics of the Market Stability Reserve. The iterative algorithm used to find the model equilibrium for each period is described in Appendix A.

We set the required expected annual return on allowances equal to 10 percent, corresponding to the assumption made in the simulations by Sandbag (2016b). This is roughly in line with the study by Neuhoff et al. (2012) who find that the marginal investors holding ETS allowances as a speculative investment require expected returns in the order of 10-15 percent. Our price sensitivity parameter b is set equal to 0.04 million tons of CO_2 per euro. Again, 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.

To fix a time path for the allowance supply, we assume that EU policy makers will adopt the European Commission’s proposal for the allocation of allowances in Phase IV of the ETS. According to this proposal the amount of allowances issued per year is reduced linearly at an annual rate of 2.2 percent of the average emissions cap in Phase II. After the end of Phase IV in 2030 this rate of reduction may be revised, but there is currently no political decision or Commission proposal to that effect. To illustrate the implications of a continuation of current policies, we therefore assume a “frozen policy” after 2030, i.e., we assume that the annual issues of allowances continue to be reduced linearly at the rate of 2.2 percent. This implies that no new allowances are issued after 2057, but allowances issued up until 2057 can be banked for use in later years.

In our baseline scenario (Scenario 1) the exogenous term $a_t - bf_t$ in our demand schedule for fossil fuels is assumed to fall by a constant annual rate of 2.2 percent, reflecting a gradual shift from fossil fuels towards renewables as well as improved energy efficiency and structural changes in the economy. In our alternative Scenario 2, intended to illustrate the potential consequences of faster long-term improvements in renewable energy technologies, we assume that the annual rate of reduction of $a_t - bf_t$ increases to 5 percent after 2060. In both scenarios the initial level and the annual rate of reduction of $a_t - bf_t$ are chosen to ensure that the model generates an allowance price for 2017 of 5.4 euros per ton, corresponding to the approximate level observed at the start of the year, and that the predicted level of emissions for 2017 corresponds to the base case forecast by Sandbag (2016c).[10]

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.

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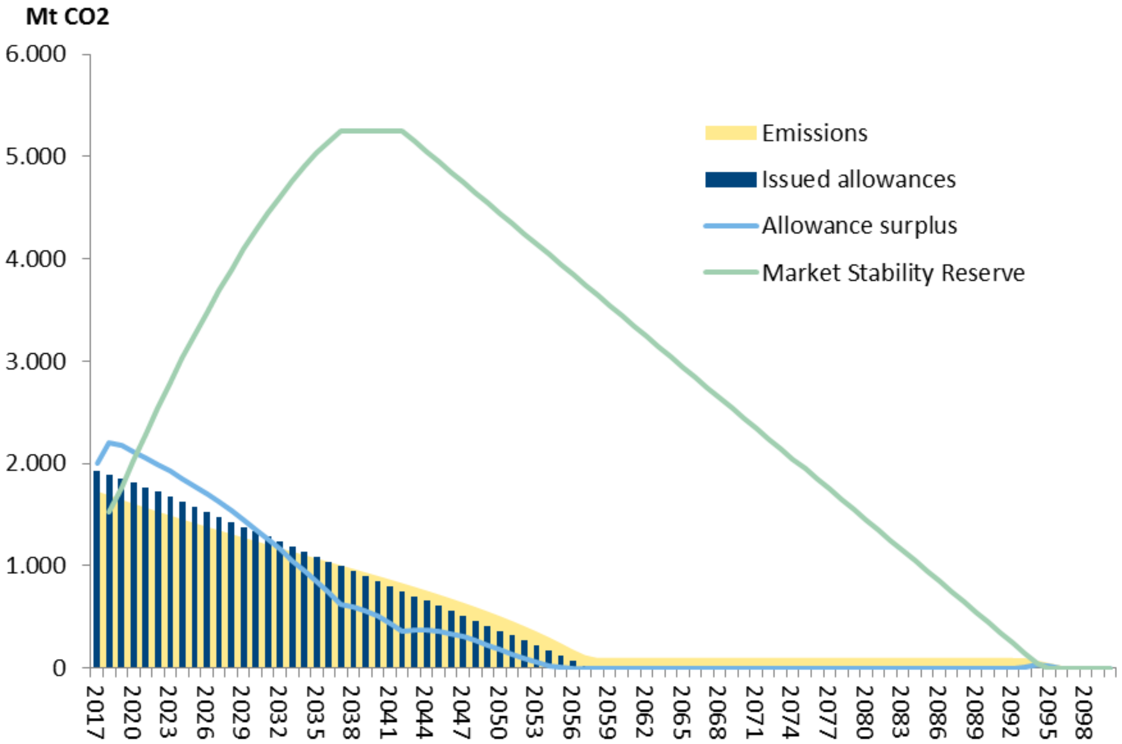
[10] Sandbag has a strong record of producing accurate emissions forecasts; see *http://carbon-pulse.com/14388/* and *http://carbon-pulse.com/2339/* .

Our calibration implies that emissions from the ETS fall by an average annual rate of 2.5 percent from 2017 to 2030 in Scenario 1. This is slightly lower than the 2.7 percent average annual reduction observed during the period 2005-2015 where emissions were dampened by the economic crisis. Between 2030 and 2050 the average annual rate of emissions reductions increases to 4.4 percent in Scenario 1, driven by the gradual phase-out of the allocation of new allowances.

To highlight the effect of the Market Stability Reserve, Figure 3 shows how the surplus of allowances available to the market would evolve in our baseline simulation if the MSR is *not* implemented. In that case a gigantic surplus would 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.

Figure 4. Evolution of emissions and the ETS allowance surplus with the MSR (Scenario 1)



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

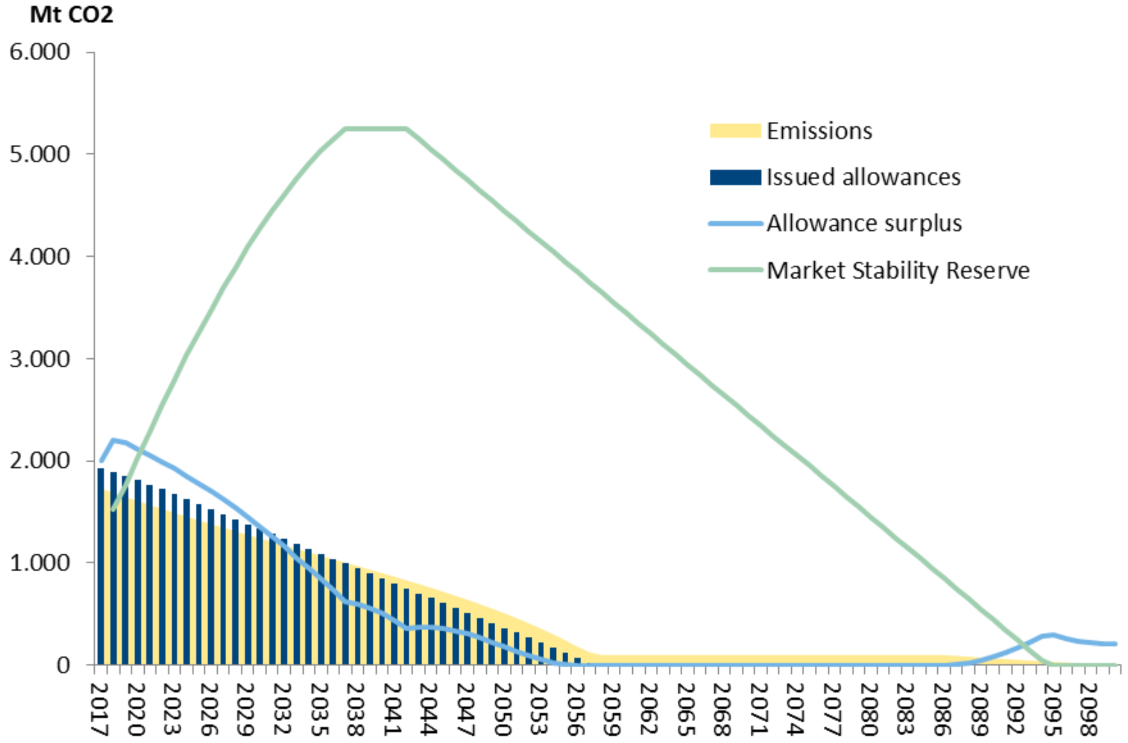
For comparison, Figure 4 depicts how the allowance surplus available to the market will develop in our baseline simulation (Scenario 1), given the existence of the MSR, as well as the dynamics of the MSR itself. We see that the MSR absorbs a large part of the allowance surplus that would otherwise emerge. The allowance surplus 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 MSR is that a marginal annulment of allowances undertaken by a single Member State in the coming years will not reduce the aggregate allowance supply by a corresponding amount until after 2096.

In our Scenario 2 illustrated in Figure 5 the demand for fossil-based energy falls more rapidly after 2060 reflecting faster progress in renewable energy technologies and/or in energy efficiency. This means that the market cannot absorb all the allowances released from the MSR from 2081 onwards. As a consequence, a permanent allowance surplus of more than 400 million tons is accumulated in the 2080s and 2090s, resulting in a collapse of the allowance price already in 2087 due to forward-looking market behaviour. Because of this permanent surplus, a marginal annulment of allowances will never be able to generate a fully corresponding fall in emissions.

Given the large anticipated investments in the development of alternative energy technologies, it is not inconceivable that our Scenario 2 will come closer to reality than Scenario 1. An evaluation of the effects of subsidies to renewable energy should therefore account for the possibility that the current rules envisaged for the MSR will not prevent the emergence of a permanent allowance surplus within the ETS.

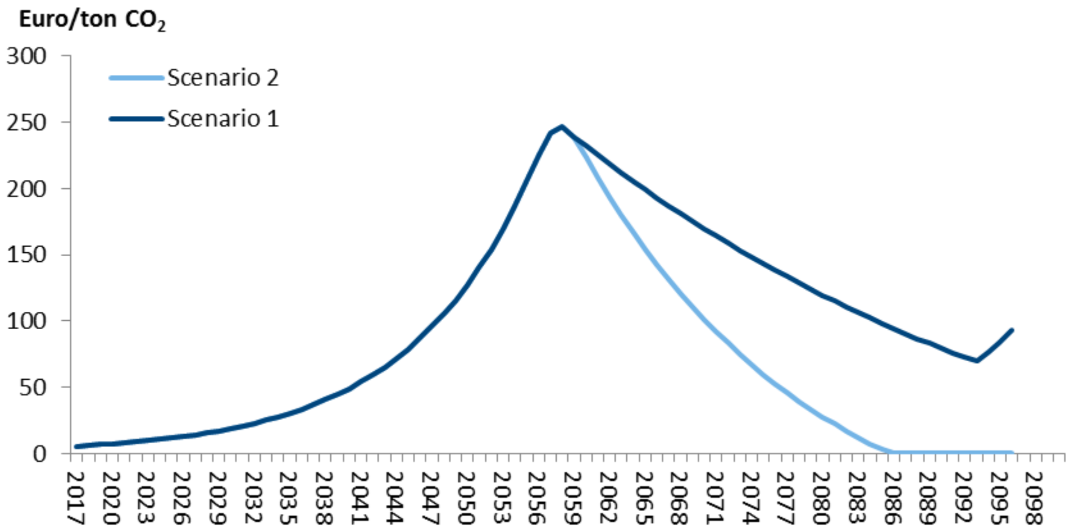
Figure 5. Evolution of emissions and the ETS allowance surplus with the MSR (Scenario 2)



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

Figure 6 shows the evolution of the allowance price in our two scenarios. Both scenarios include an allowance surplus until 2056, so until that year the price increases by 10 percent per year, implying an allowance price in 2056 of around 260 euros. After 2056 when the allowance surplus has disappeared, the price starts to fall, especially in Scenario 2. The price fall reflects that the MSR now releases a constant supply of 100 Mt of allowances from the reserve each year while the continuing demand shift away from fossil fuels tends to reduce the demand for allowances from year to year. In Scenario 1 the allowance price gradually drops to less than 70 euros in 2093 but then it recovers a bit as some investors start to hold back allowances from the market in anticipation of further price increases as the MSR is emptied. In Scenario 2 the price drops to zero from 2086 onwards, reflecting that renewable energy is now so competitive that fossil fuels are fully phased out.

Figure 6. Evolution of the ETS allowance price with the MSR



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

6. Effects of alternative climate policies on CO_2 emissions from the ETS sector

We will now use our model to compare the effects of an annulment of emission allowances (a reduction in Q) to the effects of an increase in renewable energy production, modelled as a downward shift in our parameter a assumed to be brought about through a subsidy to renewable energy.

The effects of an annulment of allowances are of considerable interest since some 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. To what extent will such a policy succeed in reducing emissions in the current situation with a large allowance surplus? And how would a comparable policy involving subsidies to renewables affect emissions?

Tables 1 and 2 provide answers to these questions, based on model simulations using our Scenario 1 as a baseline. The upper row in each table reports the *CER* implied by an annulment of 1 million tons of CO_2 allowances in 2017. The lower row shows the *CER* implied by a one-shot subsidy to renewable energy which is sufficient to crowd out 1 million tons of CO_2 emissions in 2017 (modelled as a temporary downward shift of 1 Mt in our parameter a in that year).

To illustrate the effects of the Market Stability Reserve through comparison with Table 2 below, Table 1 abstracts from the existence of the MSR.[11] In that case where the allowance surplus can be expected to last until around 2063 (cf. Figure 3), we see that the *CER* associated with the annulment of allowances is of the order of 2-3 percent and not very sensitive to the discount rate applied to CO_2 emissions when the policy horizon is 2030. In physical terms the annulment of 1 Mt of allowances in 2017 would only reduce the (undiscounted) cumulated emissions until 2030 by about 32,000 tons. This reduction reflects the negative impact on fossil fuel demand of the rise in the allowance price induced by the annulment. By contrast, the comparable policy involving an extra subsidy to renewable energy in 2017 would reduce the cumulated emissions by about 970,000 tons by 2030.

Table 1: Coefficient of Emission Reduction in Scenario 1 without MSR (marginal change)

Policy	Policy horizon: H = 2030			Policy horizon: H = 2050			Policy horizon: $H \geq 2063$		
	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$
Annulment of emission allowances	0.032	0.030	0.027	0.282	0.222	0.176	1.000	0.698	0.494
Subsidy to renewable energy	0.968	0.970	0.973	0.718	0.778	0.824	0.000	0.302	0.506

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The numbers show the present value of the change in emissions from 2017 through *H.* The allowance surplus vanishes by 2063, given the baseline calibration of the model.

When the policy horizon is extended to 2050, the *CER* associated with the annulment is about 28 percent whereas the *CER* implied by the renewables subsidy is about 72 percent when the discount rate is zero. For positive discount rates the subsidy policy is even more effective compared to the annulment policy at the 2050 horizon. On the other hand, if the discount rate is zero and the policy horizon stretches beyond 2063 where the allowance surplus disappears, the subsidy policy becomes ineffective (*CER*=0) whereas the annulment becomes fully effective (*CER*=1). But even with such a long horizon, it only takes an annual discount rate of two percent to make the subsidy policy just as effective as the annulment policy, as shown in Table 1.

In Table 2 we allow for the endogenous dynamics of allowance supply generated by the MSR. Comparing tables 1 and 2, we see that the MSR makes the annulment policy even less effective in securing emissions reductions whereas the renewables subsidy policy becomes more effective as a

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[11] The numbers in Table 1 correspond to those implied by formula (13).

result of the MSR. The explanation is the following: By reducing the allowance surplus, the annulment policy will cause fewer allowances to be transferred to the MSR, so the activation of the MSR makes more allowances available to the market in the short and medium term, thereby lowering their price and increasing emissions. The subsidy policy has the opposite effect: by increasing the allowance surplus, it causes more allowances to be absorbed by the MSR in the short and medium term, so the dampening effect of the subsidy on the allowance price becomes smaller.

Table 2: Coefficient of Emission Reduction in Scenario 1 with MSR (marginal change)

Policy	Policy horizon: $H = 2030$			Policy horizon: $H = 2050$			Policy horizon: $H \geq 2096$		
	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$
Annulment of emission allowances	0.004	0.004	0.003	0.035	0.028	0.022	1.000	0.480	0.237
Subsidy to renewable energy	0.996	0.996	0.997	0.965	0.972	0.978	0.000	0.520	0.763

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The numbers show the present value of the change in emissions from 2017 through H relative to the baseline Scenario 1 illustrated in Figure 4.

In the long term there are offsetting effects since a larger (smaller) MSR means that more (fewer) allowances will be released from the reserve in the long run. However, the model simulations show that these offsetting effects are not sufficient to reverse the conclusion that the MSR makes the annulment policy less effective and the subsidy policy more effective well beyond 2050.

In particular, since the MSR will continue to release allowances to the market as long as the allowance surplus falls short of 400 million tons, the annulment policy cannot achieve its full effect until the MSR is emptied. In Senario 1 this happens in 2096, so from that year onwards the *CER* for the annulment policy will be 1 and the *CER* for the subsidy policy will be zero if the discount rate is zero, as shown in Table 2. Not surprisingly, the table also indicates that with such a long policy horizon, it only takes a modest discount rate to make the subsidy policy more attractive.

Table 3 compares the emissions effects of the two policies in our Scenario 2 where renewable energy becomes more competitive after 2060 so that the MSR ends up with a permanent allowance surplus. We see that the subsidy policy will now succeed in reducing the undiscounted volume of emissions considerably even in the very long run (with a *CER* of about 0.94), while the annulment although the annulment policy will only have a *CER* of about 0.06 from 2056 and beyond. The annulment will delay the supply of allowances and hence prop up the allowance price for some time, which is why its *CER* is greater than zero, but ultimately it only means that the MSR ends up with a slightly smaller allowance surplus, so a marginal annulment cannot prevent the market from collapsing in the long run. In this scenario the emissions cap still becomes binding in 2056. From then until 2086 emissions are constrained to equal the 100 Mt of allowances released from the MSR, regardless of the marginal annulment of allowances in 2017. But in contrast to Scenario 1, the market cannot absorb the allowances released from the MSR after 2086, so the allowance price drops to zero in 2087. This is why the maximum impact of the annulment policy (and the minimum impact of the subsidy policy, given that $CER^R = 1 - CER^Q$) in Scenario 2 is attained already in 2056: beyond that date market developments are unaffected by the annulment.

Table 3: Coefficient of Emission Reduction in Scenario 2 with MSR (marginal change)

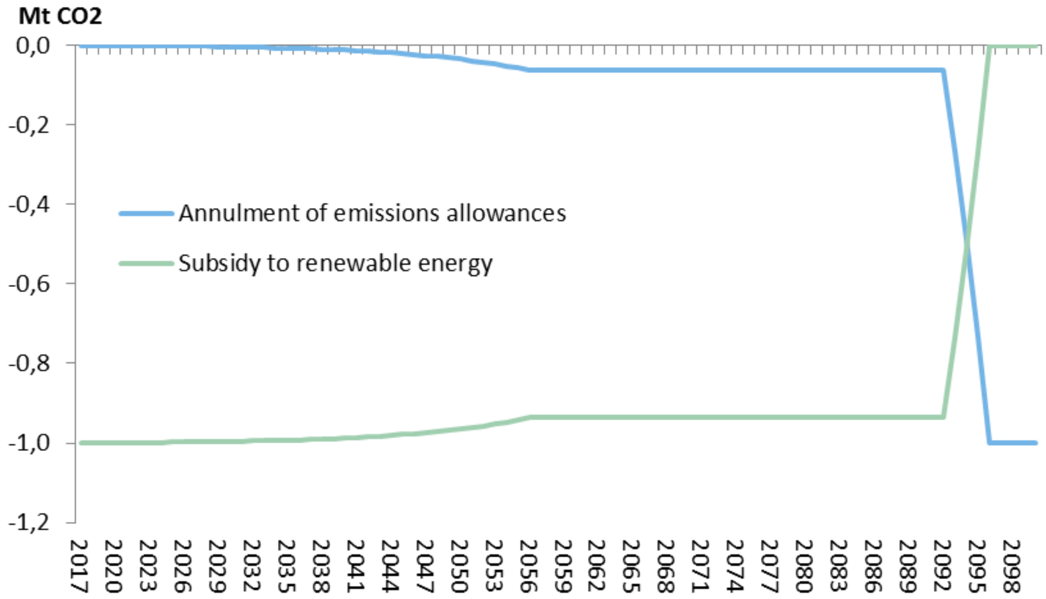
Policy	Policy horizon: $H = 2030$			Policy horizon: $H = 2050$			Policy horizon: $H \geq 2056$		
	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$
Annulment of emission allowances	0.004	0.004	0.003	0.035	0.028	0.022	0.063	0.047	0.036
Subsidy to renewable energy	0.996	0.996	0.997	0.965	0.972	0.978	0.937	0.953	0.964

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The numbers show the present value of the change in emissions from 2017 through H relative to the baseline Scenario 2 illustrated in Figure 5.

We draw two main conclusions from the tables above. First, the MSR which was intended to strengthen the ETS and reduce the need for subsidies to renewable energy actually makes such subsidies *more* effective in reducing emissions in the short and medium term until 2050, whereas annulment of allowances by individual EU Member States becomes a *less* effective policy as a result of the MSR. Second, the relative impact on emissions of the two alternative climate policies depends on the time horizon. In the short and medium term, a subsidy to renewables is much more effective in reducing emissions than annulment of allowances, but this conclusion is reversed when the time horizon becomes very long, *provided* the allowance surplus vanishes in the long term and the discount rate is zero or very close to zero. However, even in the long run it only takes a modest discount rate to make the subsidy policy more effective than the annulment policy as a means of reducing emissions, despite a binding long-run cap on emissions. Further, if the MSR ends up with a permanent allowance surplus, the subsidy policy is by far the most effective policy for all time horizons and discount rates.

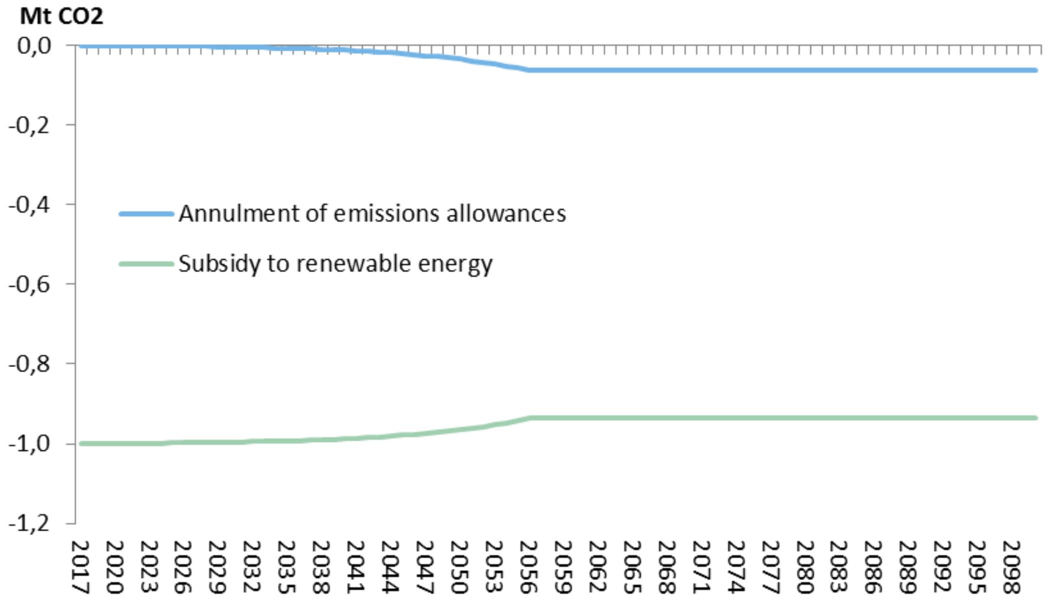
To illustrate the effects of the two climate policies in the situation most favourable to the annulment policy, figures 7 and 8 show the value of the *CER* for the two policies as a function of the policy horizon in scenarios 1 and 2, assuming a zero discount rate. Both figures account for the dynamics of the MSR. Figure 7 highlights that the annulment policy does not have any substantial effect on emissions until the mid-2090s and Figure 8 shows that this effect may never materialize if the demand for fossil energy falls significantly after 2060 as a result of technical progress in renewable energy production.

Figure 7. The Coefficient of Emission Reduction for alternative climate policies in Scenario 1



Note: The figure considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2 in 2017. The numbers show the cumulative change in emissions from 2017 up until the policy horizon H indicated on the horizontal axis.

Figure 8. The Coefficient of Emission Reduction for alternative climate policies in Scenario 2



Note: The figure considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO_2 in 2017. The numbers show the cumulative change in emissions from 2017 up until the policy horizon H indicated on the horizontal axis.

The large allowance surplus has triggered a debate among EU policy makers on the need for reform of the ETS, and in February 2017 the European Parliament proposed a tightening of the rules for Phase 4 of the ETS (covering the period from 2021 through 2030) suggested by the European Commission. According to the Parliament proposal 800 Mt of ETS allowances in the MSR should be permanently annulled and the MSR should absorb 24 percent rather than 12 percent of the allowance surplus in excess of 833 Mt during the years 2019-2022. Table 4 shows the effects of the two alternative climate policies considered above if the Parliament proposal is adopted, assuming that baseline emissions in the absence of ETS reform would evolve in accordance with our Scenario 1. Comparing tables 2 and 4, we see that the reform proposed by the EU Parliament will have only a negligible impact on the allowance market; i.e., the relative effectiveness of the two climate policies is hardly affected by the proposed reform.

Table 4: Coefficient of Emission Reduction for alternative climate policies if the European Parliament proposal for a tightening of ETS rules is adopted (marginal change)

Policy	Policy horizon: $H = 2030$			Policy horizon: $H = 2050$			Policy horizon: $H \geq 2088$		
	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$
Annulment of emission allowances	0.002	0.002	0.002	0.016	0.013	0.010	1.000	0.505	0.259
Subsidy to renewable energy	0.998	0.998	0.998	0.984	0.987	0.990	0.000	0.495	0.741

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The calculations assume the adoption of the European Parliament's proposal of February 2017 for a reform of the ETS and that baseline emissions in the absence of reform would follow Scenario 1. The numbers show the present value of the change in emissions from 2017 through H induced by the two policies.

At a meeting in February 2017 the EU Council of Ministers decided to support the Parliament proposal that the MSR should absorb 24 percent rather than 12 percent of the allowance surplus in excess of 833 Mt during the years 2019-2022. In addition, the Council proposed that any allowances in the MSR exceeding the amount of allowances auctioned during the previous year should be permanently cancelled. We have simulated the effects of the Council proposal in our model, taking Scenario 1 as the baseline. We find that in the long run the proposal will reduce the total CO_2 emissions from the ETS sector by about 10 percent relative to the baseline, but the allowance surplus will still persist until 2056. Moreover, implementation of the Council proposal would *strengthen* our conclusion that subsidies to renewable energy are more effective than annulment of allowances at the member state level, because the subsidy policy would lead to a permanent destruction of allowances in the MSR whereas the annulment policy would permanently reduce the amount of MSR allowances that is cancelled. Indeed, we find that the effects of the two policies under the system proposed by the Council become very similar to the effects in our Scenario 2 summarized in Table 3, so adoption of the Council proposal would deal the ultimate death blow to the argument behind the waterbed effect. The ongoing tripartite negotiations between the Parliament, the Council and the Commission will determine the final design of the ETS reform, but none of the proposals presented so for have the potential to eliminate the allowance surplus well before 2050.

It should be added that the annulment policy becomes more effective while the subsidy policy becomes less effective if the two policies are implemented much further into the future. In that situation there is a shorter span of years in which the two policies can influence the volume of allowances transferred to the MSR and hence the volume of allowances released from the reserve in the long run. This reduces the potential for the MSR to dampen the effect of the annulment policy and to strengthen the effect of the subsidy policy. Table B.1 in Appendix B reports the *CER* associated with the two alternative policies in Scenario 1 when they are implemented in 2035 rather than 2017. According to that table, the *CER* for the annulment policy will be 0.44 in 2050 with a zero discount rate, while the *CER* for the subsidy policy will be 0.56, so the latter policy remains the more effective one for a mid-century policy horizon.

It is also important to note that all the results presented above refer to marginal policy changes. Discrete policy changes of sufficient size may generate perverse effects. Consider an example of allowance annulment on such a scale that the allowance surplus falls below the threshold of 400 million allowances one year earlier. This will trigger the issue of an additional 100 million allowances from the MSR. Ceteris paribus the accumulated supply of allowances throughout the period until the emission cap binds has now increased; in effect, the allowance price *decreases* contrary to common intuition. The point is that larger policy measures, e.g. initiated by a coalition of countries or by the EU as a whole, may lead to unexpected results. This calls for thorough modelling and simulations when such measures are contemplated.

7. The cost-effectiveness of alternative climate policies

The analysis above suggests that, in physical terms, expansion of renewable energy production 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 Coefficients of Emission Reduction CER_H^Q and CER_H^R to answer this question. 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 shift parameter a_1 (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

$$\theta_H^Q \equiv \frac{1}{CER_H^Q}\sum_{t=1}^{H}\frac{SC_t^Q}{\left(1+r\right)^{t-1}}, \tag{17}$$

$$\theta_H^R \equiv \frac{1}{CER_H^R} \sum_{i=1}^{\tau} \frac{SC_t^R}{\left(1+r\right)^{t-1}} = \frac{1}{1-CER_H^Q} \sum_{t=1}^{H} \frac{SC_t^R}{\left(1+r\right)^{t-1}} . \tag{18}$$

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, given the discount rate r applied to these costs which will generally differ from the discount rate ρ applied to changes in physical CO_2 emissions.[12] As illustrated in the previous section, the value of CER_H^Q may be calculated by simulating our model to account for the impact of domestic climate policy on the evolution of the Market Stability Reserve.

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 in year t,

$$SW_t = CS_t + PS_t + q_t Q_t^d - \left(C_t^R - p_t\right) R_t , \tag{19}$$

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 government is entitled to issue under the rules of the ETS, p 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 a, i.e., a unit rise in R causes emissions to fall by one ton at any given allowance price q. The magnitude $C^R - p$ is the subsidy required to cover that part of the unit cost of renewable energy which cannot be covered by the market price of energy. Hence the magnitude $qQ^d - \left(C^R - p\right)R$ is the net government revenue from climate policy, consisting of the revenue qQ^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.

By simply adding net government revenue to the consumer and producer surplus in (19) we are implicitly assuming that the marginal cost of public funds is one. Strictly speaking, this assumes that the government's tax and environmental policy has already been optimized (see Kaplow (1996)). In particular, by abstracting from the impact of climate policy on government revenue from energy taxes, equation (19) implicitly assumes that the initial energy tax rate has been set to

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[12] The link between the two discount rates is given by eq. (16).

[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 (19) 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).

match the marginal external costs of energy consumption so that the marginal welfare effect of a change in energy consumption is zero. Clearly these heroic assumptions are not fully met in practice, so our simple welfare measure (19) can only give a rough approximation to the actual welfare effect of climate policy.

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 p. 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

$$\frac{\partial CS_t}{\partial p_t} = -E_t^h, \qquad \frac{\partial PS_t}{\partial p_t} = -E_t^f . \tag{20}$$

where E^h is initial household energy consumption and E^f is the initial energy consumption by firms.[14] 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. Let F^d denote the domestic consumption of fossil fuels which is also equal to total CO_2 emissions from the domestic ETS sector. Furthermore, 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. 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

$$E_t^h + E_t^f = F_t^d + R_t . \tag{21}$$

Given that the equilibrium price of energy must cover the marginal cost of fossil-based energy production, a change in the allowance price will be fully passed through to energy consumers. i.e., $dp_t / dq_t = 1$.[15] Combining this result with (20) and (21), we can use (19) 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:[16]

$$SC_1^Q = \frac{dSW_1}{dQ_1^d} = q_1 + \frac{dq_1}{dQ_1^d}\left(Q_1^d - F_1^d\right), \tag{22}$$

$$SC_t^Q = \frac{dSW_t}{dQ_1^d} = \frac{dq_t}{dQ_1^d}\left(Q_t^d - F_t^d\right) = \frac{dq_1}{dQ_1^d}\left(1+r\right)^{t-1}\left(Q_t^d - F_t^d\right), \qquad 2 \le t \le H \le T . \tag{23}$$

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[14] The results in (20) are just an application of the Envelope Theorem: When consumers have maximized their utility and firms have maximized their profit, the small change in energy consumption induced by a marginal increase in the energy price has no first-order effect on utility and profits, so the effect on utility and profits is simply equal to the rise in the cost of the initial level of energy consumption.

[15] Strictly speaking, this assumes a long-run competitive equilibrium where fossil fuel producers earn zero profits.

[16] We consider policy horizons up until year *T* when the annulment policy attains its maximum effect. Recall that *T* = 2096 in our Scenario 1 and *T* =2056 in Scenario 2.

The term $q_1 + \left(dq_1 / dQ_1^d \right) Q_1^d$ on the right-hand side of (22) is the loss of public revenue in year 1 when the government sells one less unit of allowances in that year. Using (21), we may write the term $-\left(dq_1 / dQ_1^d \right) F_1^d$ on the RHS of (22) as $-\left(dq_1 / dQ_1^d \right)\left(E_1^h + E_1^f - R_1 \right)$. The term $-\left(dq_1 / dQ_1^d \right)\left(E_1^h + E_1^f \right)$ is the welfare loss for energy consumers resulting from the higher price of energy, while the term $-\left(dq_1 / dQ_1^d \right)\left(-R_1 \right)$ 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 $\left(2 \leq t \leq T \right)$ the change in the allowance price induced by the change in Q_1^d will be $\left(dq_1 / dQ_1^d \right)\left(1 + r \right)^{t-1}$, according to (10). A higher allowance price in year t will increase the government's net revenue by the amount $\left(dq_t / dQ_1^d \right)\left(Q_t^d + R_t \right)$, where $\left(dq_t / dQ_1^d \right) Q_t^d$ is the higher revenue from the auctioning of allowances and $\left(dq_t / dQ_1^d \right) R_t$ 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 (21) 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 $\left(dq_t / dQ_1^d \right)\left[\left(Q_t^d + R_t \right) - \left(E_t^h + E_t^f \right) \right] =$ $\left(dq_t / dQ_1^d \right)\left(Q_t^d - F_t^d \right)$. This is the magnitude appearing in (23) 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. From our choice of units we have $da_1 = -dR_1$, and from (11) it follows that $dq_1 / da_1 = -dq_1 / dQ_1^d$. Using these results along with (10) and (19) through (21), and recalling that $dp_t / dq_t = 1$, we find that the social cost of expanding renewable energy production by one unit in year 1 (equal to $-dSW_t / dR_1$) is

$$SC_1^R = C_1^R - p_1 - \frac{dq_1}{dQ_1^d}\left(Q_1^d - F_1^d \right), \tag{24}$$

$$SC_t^R = -\frac{dq_t}{dQ_1^d}\left(Q_t^d - F_t^d \right) = -\frac{dq_1}{dQ_1^d}\left(1 + r \right)^{t-1}\left(Q_t^d - F_t^d \right), \qquad 2 \leq t \leq T \ . \tag{25}$$

The term $C_1^R - p_1$ on the RHS of (24) 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 $-\left(dq_1 / dQ_1^d \right) Q_1^d$ in (24) 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, the cheaper energy implied by the lower price of allowances increases the welfare of the private sector by the amount $-\left(dq_1 / dQ_1^d\right)\left(E_1^h + E_1^f\right)$, 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 (24). 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 (25). 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.

Inserting (22) and (23) into (17), we obtain the following expression for the social cost of reducing the present value of emissions by one unit through annulment of allowances:

$$\theta_H^Q = \frac{q_1}{CER_H^Q}\left[1 - \varepsilon_1 \sum_{t=1}^{H}\left(\frac{Q_t^d - F_t^d}{\tilde{Q}_1}\right)\left(1+\tilde{r}\right)^{t-1}\right],$$

$$\varepsilon_1 \equiv -\frac{dq_1}{dQ_1^d}\frac{\tilde{Q}_1}{q_1} > 0, \qquad \tilde{Q}_1 \equiv S_0 + M_0 - M_1 + Q_1, \qquad 1+\tilde{r} \equiv \frac{1+r}{1+\mu}, \tag{26}$$

where $\tilde{Q}_1$ 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).

For comparison, the social cost of reducing the present value of emissions by one unit via expansion of renewable energy supply is found by inserting (24) and (25) in (18). This gives

$$\theta_H^R = \frac{q_1}{1-CER_H^Q}\left[\frac{C_1^R - p_1}{q_1} + \varepsilon_1 \sum_{t=1}^{H}\left(\frac{Q_t^d - F_t^d}{\tilde{Q}_1}\right)\left(1+\tilde{r}\right)^{t-1}\right]. \tag{27}$$

We will now apply the formulas (26) and (27) to the case of Denmark. To do so, we need first of all numbers for the initial allowance price q_1 and the initial renewables subsidy $C_1^R - p_1$ plus an estimate of CER_H^Q. The latter number may be calculated from our simulation model, and the allowance price is set to 5.4 euros, corresponding roughly to the observed level in the beginning of 2017. The subsidy to onshore wind power needed to crowd out one ton of CO_2 emissions in Denmark was recently estimated by the Danish ministries to be 7.4 euros (Tværministeriel arbejdsgruppe (2013)). We use this number as our estimate of the renewables subsidy $C_1^R - p_1$.

In principle, we also need an estimate of the price elasticity ε_1 (which can be calculated from our model) and a forecast for the time series $\left(Q_t^d - F_t^d\right)/\tilde{Q}_1$, $t = 1,...,H$. 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 the time series $\left(Q_t^d - F_t^d\right)/\tilde{Q}_1$.

Table 5: Social cost per unit of CO_2 emission reduction in Scenario 1 (euro/ton)

Policy	Policy horizon: H = 2030			Policy horizon: H = 2050			Policy horizon: H = 2096		
	ρ = 0%	ρ = 1%	ρ = 2%	ρ = 0%	ρ = 1%	ρ = 2%	ρ = 0%	ρ = 1%	ρ = 2%
Annulment of emission allowances	1,349.06	1,459.82	1,576.12	153.74	195.35	246.05	5.40	11.25	22.78
Subsidy to renewable energy	7.43	7.43	7.43	7.67	7.61	7.57	∞	14.23	9.70

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The numbers show the values of θ_H^Q and θ_H^R calculated from the formulas (26) and (27).

With these estimates and assumptions, and using the values for CER_H^Q in Scenario 1, we obtain the estimates of social costs per unit of emissions reduction reported in Table 5 for different policy horizons and different social discount rates.

We see that for policy horizons up until 2050 the subsidy policy is by far the most cost-effective policy for all discount rates. If the horizon is extended to 2096 when the last allowance is released from the MSR, the annulment policy is the cheapest way of reducing emissions for a discount rate of zero. In this case the subsidy policy is infinitely expensive because it fails to reduce the undiscounted cumulative emissions. But even for modest discount rates, the subsidy policy becomes less expensive than annulment of allowances because it lowers emissions considerably for many years before 2096, thereby helping to postpone global warming.

Table 6: Social cost per unit of CO_2 emission reduction in Scenario 2 (euro/ton)

Policy	Policy horizon: $H = 2030$			Policy horizon: $H = 2050$			Policy horizon: $H = 2053$		
	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$
Annulment of emission allowances	1,349.06	1,459.82	1,576.12	153.74	195.35	246.05	85.27	114.39	151.81
Subsidy to renewable energy	7.43	7.43	7.43	7.67	7.61	7.57	7.90	7.77	7.67

Note: The table considers a policy experiment where 1 million allowances are annulled in 2017; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2017. The numbers show the values of θ_H^Q and θ_H^R calculated from the formulas (26) and (27).

For comparison, Table 6 shows the social cost of reducing emissions in our Scenario 2 where the MSR ends up with a permanent surplus of allowances. In this scenario the subsidy policy is many times cheaper than the annulment policy for all policy horizons and discount rates.

8. Some reflections on the political economy of allowance supply

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

$$SL = \frac{1}{2} PV_1^2 + \frac{\alpha}{2} q_1^2, \qquad \alpha > 0, \tag{28}$$

where PV 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 H does not exceed the time T when the emissions cap becomes binding. In that case future allowance prices are proportional to the current allowance price q_1 (cf. (10)), and hence we do not need to incorporate them explicitly in the loss function (28), since any concern about future allowance prices is reflected in the size of the parameter α. Notice also that the size of α will be 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.

Like before, we will consider the effects of the two domestic policy instruments Q_1^d and R_1. Recalling that the renewable energy supply R_1 causes a corresponding downward shift in fossil fuel demand so that the fossil fuel demand schedule for year 1 may be written as $a_1 - R_1 - b\left(f_1 + q_1\right)$, we can restate the equilibrium condition (11) for the allowance market as

$$\sum_{t=1}^{T}\left\{a_t - b\left[f_t + \left(1+r\right)^{t-1} q_1\right]\right\} = R_1 + X \quad , \tag{29}$$

where X is the cumulative EU-wide supply of emission allowances from year 1 to year T, including any initial allowance surplus. Equation (29) defines q_1 as an implicit function of $R_1 + X$ with the derivative stated in (12), i.e.,

$$q_1 = q\left(R_1 + X\right), \qquad q' = -\beta, \qquad \beta \equiv \frac{r}{b\left[\left(1+r\right)^T - 1\right]} > 0\,. \tag{30}$$

Using (30) and our definition of CER_H^Q stated in (13), we may write the present value of emissions over the policy horizon H as

$$PV_1 = g\left(R_1 + X\right) - R_1,$$

$$g\left(R_1 + X\right) \equiv \sum_{t=1}^{H}\left\{\frac{a_t - b\left[f_t + \left(1+r\right)^{t-1} q\left(R_1 + X\right)\right]}{\left(1+\rho\right)^{t-1}}\right\}, \tag{31}$$

$$g' = b\beta\sum_{t=1}^{H}\left(\frac{1+r}{1+\rho}\right)^{t-1} = \frac{r}{\tilde{r}}\left[\frac{\left(1+\tilde{r}\right)^H - 1}{\left(1+r\right)^T - 1}\right] \equiv CER_H^Q > 0,$$

With the notation in (30) and (31) the social loss function (28) can be written in the form

$$SL = \frac{1}{2}\left[g\left(R_1 + X\right) - R_1\right]^2 + \frac{\alpha}{2}\left[q\left(R_1 + X\right)\right]^2. \tag{32}$$

Taking the renewables-policies of individual member states as given, we imagine that EU policy makers choose X with the purpose of minimizing the social loss in (32). Given the expressions for the derivatives q' and g' stated in (30) and (31), the first-order condition for the solution to this problem is

$$\begin{gathered} \partial SL / \partial X = 0 \quad \Rightarrow \\ CER_H^Q \left[g\left(R_1 + X \right) - R_1 \right] - \alpha\beta q\left(R_1 + X \right) = 0, \end{gathered} \tag{33}$$

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 (33) 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 (33), and the allowance price will be driven above the level implied by (33). 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 (33) is still satisfied. 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 (30), (31) and (33) this will trigger the following subsequent adjustment of aggregate allowance supply at the EU level:

$$\frac{\partial X}{\partial R_1} = -1 + \frac{CER_H^Q}{\left(CER_H^Q \right)^2 + \alpha\beta^2} \quad . \tag{34}$$

We see from (34) 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 (30), (31) and (34) that

$$\frac{dPV_1}{dR_1} = CER_\tau^Q - 1 + CER_\tau^Q \frac{\partial X}{\partial R_1} = -\frac{\alpha\beta^2}{\left(CER_\tau^Q \right)^2 + \alpha\beta^2} < 0 \, , \tag{35}$$

$$\frac{dq_1}{dR_1} = -\beta \left(1 + \frac{\partial X}{\partial R_1} \right) = -\frac{\beta CER_\tau^Q}{\left(CER_\tau^Q \right)^2 + \alpha\beta^2} < 0 \, . \tag{36}$$

In contrast to an annulment of allowances, we see from (35) 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. This is intuitive: by reducing emissions at any given allowance price, an increase in renewable energy supply improves the trade-off between the 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. cf. (36)).

This analysis assumes that the EU can act after the national policies of the individual member countries have been set. In practice this may only happen with a considerable time lag. Our stylized model is intended to illustrate a situation where EU policy makers can use their supra-national powers to determine rules which modify or nullify policies decided at the member state level. The MSR is an example of such a supra-national policy that modifies the impact of member state climate policies.

Of course, these results should not be taken too literally since they derive from an extremely simplified description of EU policy making. However, on the plausible assumption that EU policy makers do care about the level of energy prices as well as the level of emissions, the political economy analysis in this section tends to support 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.

9. Conclusions

This paper has set up a simple, partial-equilibrium model of the European Emissions Trading System with forward-looking market behaviour. The model is calibrated to market data for 2017 and incorporates the current and planned future rules for the allocation of emission allowances, including the Market Stability Reserve to be established from 2019. Given current and planned future policies, the model indicates that a surplus of allowances available to the market will persist until some time in the 2050s. In our baseline “frozen policy” scenario the Market Stability Reserve will continue to release accumulated surplus allowances until the mid-2090s, and in an alternative not implausible scenario there will be a permanent allowance surplus resulting in a market collapse some time in the mid-2080s.

Against this background we found that a marginal annulment of allowances by an individual EU member country will have very little effect on total CO_2 emissions until the end of the century and there is a risk that the effect will remain negligible forever if the market collapses. By contrast, a subsidy to renewable energy which reduces the demand for ETS allowances will have a substantial dampening effect on emissions until the end of the century and a permanent effect if the allowance surplus never vanishes. Even at the very low current allowance price, we found that subsidies to renewables are a more cost-effective way of curbing emissions than annulment of allowances at the individual EU member state level as long as future changes in emissions are discounted at a modest discount rate. Paradoxically, our analysis indicates that this conclusion is strengthened by the introduction of the Market Stability Reserve.

These results were derived on the assumption that political decisions at the EU level to allocate emission allowances are not affected by the price of allowances. However, we argued that the supply of allowances is likely to reflect a political trade-off between a desire to cut emissions and a desire to keep energy prices for EU businesses and households low. Based on this hypothesis, we set up a stylized political economy model of the emissions trading system to show that annulment of allowances at the individual member state level is likely to be offset by an increase in allowance supply decided at the EU level, whereas expansion of renewable energy supply will induce EU policy makers to issue fewer emissions allowances because it tends to reduce energy prices by reducing the price of allowances. In this way political economy factors tend to strengthen the effects of subsidies to renewables and to weaken the effects of an annulment policy even further.

Overall, our findings contradict the frequent claim that the European Emissions Trading System makes subsidies to renewable energy ineffective. On the contrary, if the policy horizon is 2030 or 2050, an expansion of renewable energy supply will be far more cost-effective than the annulment of ETS allowances that several EU Member States will be permitted to undertake as part of their contribution to the EU climate policy targets for 2030.

We should stress that this conclusion refers to an annulment of allowances of limited size undertaken by an individual member state. A large-scale permanent withdrawal of allowances decided at the EU level (or undertaken by a large coalition of member states) could eliminate the allowance surplus within a reasonable time horizon, thereby driving the allowance price closer to the social cost of carbon and making subsidies to renewables redundant. Establishing a realistic carbon price is clearly preferable to massive subsidization, and we see the analysis in this paper as a strong argument for such a reform of the ETS. But if a comprehensive reform is not forthcoming, national subsidies to renewables will be a legitimate ingredient in European climate policy for some time to come and should not be dismissed by reference to a waterbed effect which might materialize towards the end of the century, if at all, given current ETS policies.

APPENDIX A: Solution algorithm

This appendix describes the algorithm used to solve our model of the ETS specified in section 3. First some notation: Consider the period from year *i* through year *j* and let allowance prices for year *t* in that period be given by $q_t = q_i(1+r)^{t-i}$. Take allowance prices before year *i* as given. The cumulative allowance surplus in year *j* is then a function of q_i, i.e. $S_j(q_i)$, where the surplus is derived as in (2). Define $\hat{q}_i(j)$ such that $S_j\big(\hat{q}_i(j)\big) = 0$ given the assumed exogenous time path for the allocation of new allowances (Q). Now, an equilibrium of the model is found through the following steps:

1. Calculate $\hat{q}_1(j)$ for all $j=1,\dots,T$ where T is sufficiently far out in the future such that all allowances are used.
2. Let v be the latest year that ensures $S_t\big(\hat{q}_1(v)\big) \geq 0$ for all $t = 1, \dots, v$.
3. Fix $q_1 = \hat{q}_1(v)$ and $q_t = \hat{q}_1(v)(1+r)^{t-1}$ for all $t = 2, \dots, v$.
4. Repeat step 1 through 3 where year 1 is replaced by year $v+1$.
5. Step 4 is repeated until $v = T$.

APPENDIX B: Effects of alternative climate policies implemented in 2035

As mentioned in Section 5 the annulment policy becomes more effective and the subsidy policy less effective if the policies are implemented further into the future, thereby leaving less time for the dynamics of the MSR to influence the allowance surplus. This is illustrated in Table B.1 where the two policies are implemented in 2035. The policy changes are assumed to be unanticipated, so they have no effect on allowance prices and emissions before 2035.

Table B.1: Coefficient of Emission Reduction in Scenario 1 with MSR (marginal change)

Policy implemented in 2035	Policy horizon: H = 2050			Policy horizon: H =2096		
	$\rho = 0\%$	$\rho = 2\%$	$\rho = 4\%$	$\rho = 0\%$	$\rho = 2\%$	$\rho = 4\%$
Annulment of emission allowances	0.444	0.369	0.311	1.000	0.708	0.532
Subsidy to renewable energy	0.556	0.631	0.689	0.000	0.292	0.468

Note: The table considers a policy experiment where 1 million allowances are annulled in 2035; alternatively renewable energy is subsidized to the extent needed to crowd out 1 Mt CO2 in 2035. The numbers show the present value of the change in emissions from 2035 through H relative to the baseline Scenario 1 illustrated in Figure 4.

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