Centre for Climate Change Economics and Policy

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System responsiveness and the European Union Emissions Trading System

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The 2013 Dahrendorf Symposium on 'Changing the European Debate: Focus on Climate Change' took place at the Akademie der Künste, Pariser Platz, Berlin, on 14 and 15 November 2013. The symposium is an initiative of the Hertie School of Governance, the London School of Economics and Political Science (LSE) and Stiftung Mercator. Its objective is to shine a light on how academia can have a productive influence on socio-political discourse and aims to offer European perspectives on the most pressing global challenges of our time. Further details about the symposium can be found at: http://www.dahrendorf-symposium.eu/

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funders. This paper is based on a presentation at the 2013 Dahrendorf Symposium.

Executive Summary

Whether the European Union Emissions Trading System (EU ETS) needs to be reformed, and if so how, is an important issue in the European policy debate.

A key question is whether the objective of the EU ETS is solely to bring down greenhouse gas emissions at least cost, which it is achieving, or whether it is also intended to deliver a price signal that induces low-carbon innovation, which it is not achieving at any significant level. The European Union Emissions Trading Directive is not explicit about the latter objective, giving those who argue either that reducing greenhouse gas emissions is the only aim of the EU ETS, or that a reform of the system is therefore not necessary, a relatively good opportunity to do so.

This policy paper argues that reforming the EU ETS is justified whether or not one believes that stimulating low-carbon innovation is one of its objectives. In particular, this paper argues that a large part of the problem is that market agents believe there is an excessive market imbalance and, consequently, the price of allowances (EUAs) will remain low even when the European economy returns to growth. This arises because the regulator (the European Commission) is unable to respond to downward price shocks by withdrawing allowances.

The crucial point is to incorporate a responsiveness mechanism into the EU ETS so that it would change the current perception of market agents that the price of EUAs can remain low for long periods after unexpected price shocks. A responsiveness mechanism would encourage regulated businesses to bank EUAs while the price is low.

To be effective, the mechanism would have to be based on a transparent system of rules for determining when EUAs should be injected or withdrawn. The price trend over a given time period would appear to be the most transparent and simple trigger for a withdrawal or injection of EUAs. The mechanism is similar in spirit to Article 29(A) of the European Union Emissions Trading Directive which enables the injection of EUAs when, for more

than six consecutive months, the price of EUAs is higher than the average price during the preceding two years. However, in the case described here, a change in price trend triggers intervention. In particular, the mechanism would enable the withdrawal of EUAs, when for a given period (that which is stipulated in the current Article may or may not be the correct time period), the price trend is significantly lower than during a preceding pre-determined time period.

Once a withdrawal or injection of EUAs has been triggered, the European Commission would have to calculate the volume of EUAs to be withdrawn. This calculation should be based on the time remaining in the current market phase, the number of EUAs that remain to be auctioned, and future projected emissions.

If the mechanism described here is implemented, it could induce self-adjusting behaviour by market agents. When the price of EUAs either persistently rises or falls over a given time period (e.g. 6-12 months), businesses will expect an intervention in the market. In particular, when there is a relatively higher rise in the price trend, businesses would face a situation where they expect an injection of EUAs. So, for those businesses in possession of an excess of EUAs, it would seem to be in their interest to sell; for those businesses having a shortage of EUAs, it would seem to be in their interest to wait. When there is a relatively large decreasing price trend, businesses would face a situation where they expect withdrawal of EUAs. So, for those companies that are short of EUAs, it would seem to be in their interest to buy; for those businesses having an excess of EUAs it would seem to be in their interest to wait.

1 Introduction

Whether the European Union Emission Trading System (EU ETS) needs to be reformed - and if so how - is an important issue in the European policy debate.

The debate about reform was prompted by a marked and persistent drop in the price of allowances (EUAs) from €30 in January 2008 to €4.50 in July 2013. There is a broad consensus that the weak price of EUAs has been caused by a number of factors: the economic recession; the overlap with other policies, such as renewable energy and energy efficiency policies; a pronounced short-termism;[1] and general uncertainty about long-term emission targets within the European Union and internationally (Aldy & Stavins, 2012; Neuhoff et al., 2012; Egenhofer et al., 2012; Van den Bergh et al., 2013; Piris-Cabezas & Lubowski, 2013).

There appears to be much less consensus about whether the current low price is per se a problem that warrants regulatory reform (CEPS, 2013; Grosjean et al., 2013; Verdonk et al., 2013). Differences of opinion about this point usually originate from different perceptions about the implicit objectives of the EU ETS. For some, the EU ETS was established purely to reduce greenhouse gas emissions at least cost (Goulder, 2013, and references therein). Others expected the EU ETS to not only deliver greenhouse gas emission reductions, but also to provide a price signal that induces technological innovation (for example, see the Ministerial call for ambitious and immediate low-carbon action by the European Union; EC, 2013).

There is an ongoing debate about whether stimulating low-carbon investment is a stated aim of the EU ETS (CEPS, 2013; Grosjean et al., 2013). This has made the debate about its reform polarised and political, and distracted from the real issue: the lack of 'responsiveness' in the system. This policy paper argues that reforming the EU ETS is justified whether or not one believes that stimulating low-carbon innovation is an objective of the

[1] 'Short-termism' means an excessive short-term focus by some corporate leaders, investors, and analysts, combined with insufficient regard for long-term strategy. Such a view can undermine the market's credibility, and discourage long-term investments.

EU ETS. In particular, the paper argues that a significant problem for the EU ETS is market agents believing there is an excessive market imbalance, which means that the price of EUAs will remain low even when the economy of the European Union returns to growth. This arises because the regulator (the European Commission) is unable to respond to unexpected downward price shocks by withdrawing EUAs.[2]

Intuition suggests that making the system more responsive to changes in economic circumstances has appeal. This is supported by research which shows that loosening the cap when the price of EUAs is extremely high and tightening it when the price is extremely low could lower the expected cost of achieving emission reduction targets.[3]

In an attempt to increase the price of EUAs and restore credibility in the EU ETS, the European Parliament has passed a proposal to temporarily withhold, or 'backload', 900 million new EUAs from the system, instead releasing them into the market at an unspecified point before 2020. However, as analysis in this paper shows, backloading is insufficient because although it will mean that EUAs will be scarcer in the short term, there is no impact on the long-term market price expectation. Even a one-off measure that permanently withdraws EUAs is insufficient because, although it will have an impact on the market price expectation, and so the price of EUAs would rise, its one-time nature is limiting. Structurally, such a measure still leaves the EU ETS vulnerable to unexpected economic and technological shocks in the future. Hence, one-off measures treat the symptom of the problem – weak price – rather than the cause – a lack of system responsiveness.

Currently, the European Commission cannot intervene in the EU ETS in response to unforeseen economic or technological shocks in a way that alters market price expectation. There is a wide range of conceivable mechanisms that could achieve this. A supply

[2]The EU ETS has a provision for addressing excessive prices of EUAs; Article 29a of the European Union Emissions Trading Directive, provides for the possibility of making more allowances available when "for more than six consecutive months, the allowance price is more than three times the average price of allowances during the two preceding years".

[3]This relates to the academic literature that investigates price-quantity combinations (Weitzman, 1974; Hepburn, 2006; Gruell & Taschini, 2011; Goulder & Schein, 2013).

management system that can inject and withdraw permits from the market, based on an agreed set of rules, is appealing to a broad range of stakeholders because it would be non-discretionary and would require minimal intervention in the market.

The crucial point about incorporating a responsiveness mechanism into the EU ETS is that it would change the perception that the price of EUAs could remain low for long periods after a severe change in the economic circumstances.[4] This would encourage regulated businesses to bank EUAs when the price is low, and would have an upward effect on the price. Using the 2008 economic recession as an example, had such a responsiveness mechanism existed prior to the downturn, the latent threat that the European Commission could have withdrawn EUAs in response to their rapidly falling price would have changed market perceptions, encouraged banking of EUAs, mitigated the price collapse and caused the EUA price to follow the economic recovery more closely, rather than stagnating as it has done.

This paper gives an overview of how a responsiveness mechanism could work. It suggests that a rules-based reserve management system could be designed using a double trigger: a price-trend trigger indicating the timing of the intervention, and a volume-based trigger indicating the magnitude of the intervention.

2 What is the issue, if there is an issue?

The low price of EUAs in the EU ETS is not necessarily a problem. In a cap-and-trade system, the number of EUAs is, by design, highly inelastic in the short term, changing only as a result of government policy decisions (for example, a one-off allowance removal). With highly inelastic supply, shifts in demand can cause significant price changes. However, the ups and downs of the EUA price can play a beneficial role.

[4] Given the large uncertainties prevalent in carbon policy, we are suggesting a policy that is itself contingent on other factors.

During economic downturns, the demand for EUAs will fall, which also causes their price to fall. The lower price is desirable because it softens the impact of the pollution regulation on businesses during the difficult economic times. This is what happened in 2008: the economic recession, coupled with overlapping policies,[5] put downward pressure on the demand for EUAs and, unsurprisingly, their price fell.

The current supply-demand imbalance in the EU ETS is expected to persist until the end of the third trading period in 2020. Although rules allow EUAs to be banked for use in future phases after 2020, the persistence of the low price even though many Member States are undergoing economic growth again indicates that the market as a whole believes that the system is significantly oversupplied even over the long term. Research by Piris-Cabezas & Lubowski (2013) shows that, without intervention,[6] the existing oversupply of EUAs will be absorbed very slowly and so EUA prices will remain relatively low for longer; not reaching a level comparable with the pre-2008 prices until 2018/2019. The large oversupply has distorted the orderly functioning of the EU ETS so that, despite economic growth within Europe since the 2008 crisis, there has been no upturn in the price of EUAs. This is muting the incentive for businesses to reduce emissions.[7] What seems to be missing is the ability of the policy regulator to respond to unforeseen changes in the economic circumstances[8] that generate downward price pressure. Lack of system responsiveness depresses demand to bank or purchase EUAs and, consequently, keeps their price low.

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[5]New energy efficiency or renewable obligations, as currently contemplated, are liable to affect future allowance demand. Economic theory as well as recent experience shows that policy interactions can significantly reduce both the environmental effectiveness and cost-effectiveness of policies. This is particularly important in the case of cap-and-trade (Lecuyer & Quirion, 2013).

[6]The analysis by Piris-Cabezas & Lubowski (2013) suggests that the market is currently behaving as if the surplus will be absorbed very slowly, which is only consistent with a very high discount rate from holding and banking allowances - given future post-2020 targets and assuming that information about those future targets is absorbed incrementally over time.

[7]In other words, the inter-temporal efficiency of the system is undermined by the large oversupply.

[8]More generally, what seems to be missing is the ability of the policy regulator to respond to changes in economic circumstances, technological advancement and complementary policies.

3 The exam question: A rules-based 'responsiveness' mechanism

The European Commission has attempted to increase the price of EUAs by temporarily withdrawing, or backloading, 900 million from the market. The EUAs will be released back into the system at an unspecified date before 2020. The backloading proposal means that EUAs will be scarcer in the short term, which some analysts predict will increase their price by approximately 35 per cent to €6 by the end of 2014 (Thomson Reuters, 2014). However, there will be relatively little impact on the long-term market price expectation, so backloading alone will be insufficient to restore the proper functioning of the market.

Even if the backloaded EUAs were permanently withdrawn from the EU ETS, such one-off measures leave the system vulnerable to future unexpected economic and technology shocks. Hence, one-off measures address the symptoms of structural weakness - low EUA prices - but not the cause: the perception of market participants that the price will remain low due to oversupply and that the regulator cannot intervene to change the situation.

In order to change the perception of market participants, the system has to have – and be known to have - the ability to respond to situations of significant oversupply. Article 29(A) of the European Union Emissions Trading Directive allows for the possibility for the European Commission to respond when, for more than six consecutive months, the EUA price is higher than the average price during the preceding two years, by injecting new EUAs into the system. We propose the introduction of an article that is similar in spirit and allows for the possibility of withdrawing EUAs. Figure 1 shows the impact that such a responsiveness mechanism could have on the price of EUAs.

The inability of the EU ETS to respond to the downward price shock depresses the incentive to bank or purchase EUAs. This is what we observe in Figure 1 from 2009 onwards. EUA prices stay low until the oversupply is entirely absorbed by the system, as the purple line shows. However, as soon as a responsiveness mechanism, as described here, is introduced, the price of EUAs rises more quickly because of the combined effect of a withdrawal of EUAs and the increased incentive the mechanism creates for businesses to bank EUAs while their price is low in anticipation of a possible withdrawal.[9] The green line in Figure 1 shows this result.

Figure 1: **Modeled EUA price from 2014 to 2020 with and without 'responsiveness'**

Key

Blue line – Historic EUA prices 2008 to 2013

Purple line – Simulated EUA prices 2013-2020 where there is no responsiveness mechanism adopted (and no one-time permanent removal of permits)

Green line – Simulated EUA prices 2013-2020 where a responsiveness mechanism is incorporated in 2013 (an exemplary withdrawal of allowances is made in 2014 and 2016)

Note* a similar simulation of EUA prices 2013-2020 'without responsiveness' can be found in Piris- Cabezas & Lubowski (2013).

[9]It is important to note that market participants should have confidence that the desired interventions will happen. A transparent, rules-based mechanism would maximise the confidence in an intervention.

There are a number of options for the design of a responsiveness mechanism for the EU ETS. A natural approach would be to index the emissions cap to an economic activity indicator. Indexing will adjust the emission cap to changes in the economy and, ultimately, make the cap respond to shocks. An indexed policy could be a better option than a fixed cap policy if the post-shock cap can be adjusted properly,[10] but that would require an appropriate indicator. However, as Newell and Pizer (2008) pointed out, identifying the proper economic activity indicator is a complex task: the indicator must capture the direction and the right intensity of the shock.[11] The identification of the proper (under- or oversupply) indicator is crucial to the proper functioning of the mechanism.

Instead of indexing the cap to an economic indicator, we suggest a responsiveness mechanism such that the over- and undersupply of EUAs is controlled by the regulator in line with a transparent set of rules.[12] The rules would put in place a double trigger system, whereby the price trend (trigger 1) is used to identify if and when EUAs need to be withdrawn or injected from the system and a quantity-based trigger (trigger 2) determines the magnitude of the withdrawal or injection. The responsiveness mechanism proposed adjusts the supply of EUAs by depleting or replenishing a reserve, and can be therefore referred to as a rules-based reserve management mechanism. We do not suggest rules that generate price bounds based on administrative discretion, such as a price floor or a price ceiling. Rather, we propose a trigger based on the daily rate of return over a past period (e.g. 6-12 months).

[10]Unexpected fluctuations in economic activity and technology development can result in shifts of the trajectory of expected least-cost emissions reduction over time. Adjustments are then required in order to restore the optimality of the policy.

[11]Ellerman & Wang (2003) and Marschinski & Edenhofer (2010) show that the incentive for a lasting transformation of the regulated sectors is not necessarily stronger if an economic indicator is applied (for example, with an index or intensity target). Overall, their results suggest that indexed policies have potentially only modest benefits.

[12]The Technical Appendix to this paper provides an analysis of market behavior with and without a responsiveness mechanism. The analysis shows how market imbalances disrupt the orderly functioning of the market for EUAs. Based on the analysis, the mechanism described here is intended as a cost-effective and efficient means to reinstate the orderly functioning of the market.

The mechanism could borrow from Article 29(A) which enables the injection of EUAs when, for more than six consecutive months, the EUA price is higher than three times the average price of EUAs during the preceding two years. We propose a similar rules-based mechanism; however the change in trend triggers intervention. More precisely, the mechanism would enable the withdrawal of EUAs when, for a specified period (that stipulated in Article 29(A) may or may not be the correct time period), the price trend is significantly lower than during a preceding and pre-determined reference time period.

The decision to intervene should be based on the price trend because:

- A price-trend trigger is the most transparent and simple indicator available.
- Regulated entities can try to exploit regulatory changes to their own advantage. A price-trend trigger cannot be easily manipulated - in particular when the trend is observed over a period of 6-12 months. A purely quantity-based trigger provides firms with an incentive to distort investment decisions in order to signal high under- or over-compliance and prepare the ground for more or fewer EUAs being released for subsequent trading periods (Harstad & Eskeland, 2010).

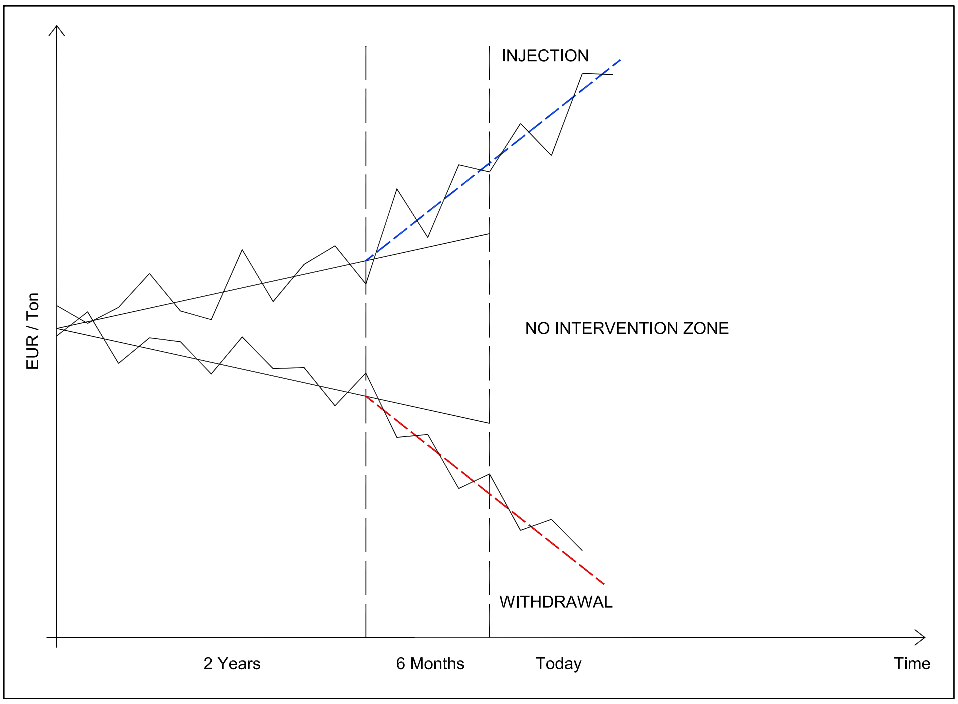
Once a withdrawal or injection of EUAs has been triggered, the European Commission would have to calculate the volume to be withdrawn. This calculation would be based on the time remaining in the current market phase, the number of EUAs that remain to be auctioned, and future projected emissions.[13]

If the responsiveness mechanism described here is implemented, it will induce self-adjusting behaviour by market participants. When the price of EUAs either rises or falls over the specified period more quickly than the reference period, businesses will expect an intervention in the market (see dashed lines in Figure 2). In particular, when there is a relatively big rise in the price trend, businesses would expect an injection of EUAs (see the blue line

[13] We show in the Technical Appendix that the price of EUAs can be decomposed into (i) the marginal abatement cost and (ii) the market implied under- or over-compliance level. This last component is used for the calculation of the volume of EUAs to be withdrawn from or injected into the system.

in Figure 2). So, for those businesses possessing an excess of EUAs, it would be in their interest to sell in advance of the injection; for those businesses having a shortage of EUAs, it would be in their interest to wait until the injection. When there is a relatively big fall in the price trend, businesses would expect a withdrawal of EUAs (see red line in Figure 2). So, for those businesses having a shortage of EUAs, it would be in their interest to buy in advance of the withdrawal; for those businesses possessing an excess of EUAs, it would be in their interest to wait until the withdrawal.

Figure 2: **First trigger of the responsiveness mechanism – price trends for intervention**



Key

Dashed red line – scenario in which, for more than six consecutive months, the EUA price trend is lower than three times the price trend of EUAs during the two preceding years → withdrawal of EUAs

Dashed blue line - scenario in which, for more than six consecutive months, the EUA price trend is higher than three times the price trend of EUAs during the two preceding years → injection of EUAs

These dynamics (i) determine the level of intervention (quantity of EUAs injected and withdrawn); and (ii) significantly reduce the level of intervention required to change the behaviour of market participants.

This behavior is likely to mean that the mechanism will trigger only when there are significant and unforeseen price shocks. Stakeholders would therefore be reassured that such a mechanism would not result in a highly interventionist approach by the European Commission, but rather, injection or withdrawal of EUAs would happen only infrequently and in exceptional circumstances.

4 Conclusions and policy recommendations

- Reforming the EU ETS is necessary whether or not one believes that the system should stimulate low-carbon innovation.
- Temporary and permanent one-off measures should be replaced by a mechanism that allows the system to automatically respond to changes in economic circumstances, technological advancement and complementary policies.
- We suggest a mechanistic response through which EUAs are withdrawn from or injected into the market, based on a pre-specified set of rules. We call this system a rules-based reserve management mechanism.
- We propose that the timing of an intervention should be dependent on price development over a specified timeframe (e.g. 6-12 months). Such a design is preferable to discretionary one-off measures because a trigger based on a price trend is transparent, is simple to explain, and provides clarity for market participants.
- Once a withdrawal or injection of EUAs has been triggered, the European Commission would have to calculate the volume of EUAs to be withdrawn. This calculation would be based on the time remaining in the current market phase, the number of EUAs that remain to be auctioned, and future projected emissions.
- If a second objective of the EU ETS is to send a price signal that is strong enough to promote innovation, the proposed rules-based reserve management mechanism could be effectively used to enforce a price target zone. A price target zone would depend on the combined objectives of reducing carbon emissions at the least cost and promoting innovation. However, the European Commission would need to be explicit about these objectives and how it prioritises them. Whether a price target zone is desirable depends on these explicit objectives.

Appendix

This paper considers an emissions trading system in a stochastic equilibrium model. The model allows for a decomposition of the allowance price into a sum of two components: The marginal cost of abatement and a distortion term. This last term represents the market imbalance. We propose a policy that addresses the excessive market imbalance, mitigates the distortionary effect the imbalance has on the EU ETS, and, ultimately, restores the orderly functioning of the allowance (EUA) market.

We consider a continuum of atomistic traders (players) and a continuous time interval $[0, T]$. In an emissions constrained economy, at time T every player has to comply with the regulations by offsetting her total emissions with EUAs.

Each player has a (subjective) expectation about her future emission and future EUA positions, as well as about future price developments. Let the stochastic process $Y = (Y_t)_{t\in[0,T]}$ incorporate all relevant decision variables; the process Y will be specified later in the text. In order to account for the heterogeneity in the players' market expectations, we consider the following setup: for each player i we consider a filtered probability space $\big(\Omega, \mathcal{F}, (\mathcal{F}_t^i)_{t\in[0,T]}, \mathbb{Q}^i\big)$, where Ω is a non-empty set, $\mathcal{F}$ a σ-algebra on Ω and $\mathbb{Q}^i$ is the probability measure of player i. Both Ω and $\mathcal{F}$ are identical for all players. We define the filtration $(\mathcal{F}_t^i)_{t\in[0,T]}$ of $\mathcal{F}$ to be the natural filtration of the process Y under $\mathbb{Q}^i$. That is, all players observe the same state Y_t at time t. However, their assessment of the future market development differ. This is what we realistically observe on every market. We also consider an objective measure $\mathbb{P}$ on $(\Omega, \mathcal{F})$ and accordingly denote by $(\mathcal{F}_t)_{t\in[0,T]}$ the natural filtration of Y under $\mathbb{P}$. For any random variable x, we refer to $\mathbb{E}^{\mathbb{Q}^i}[x]$ as player i's *projection* of x or *projected* (value of) x. We denote by $\mathbb{E}_t^{\mathbb{Q}^i}$ the projection conditioned on $\mathcal{F}_t^i$, i.e. $\mathbb{E}_t^{\mathbb{Q}^i} = \mathbb{E}[\cdot|\mathcal{F}_t^i]$. Accordingly, we denote by $\mathbb{E}_t^{\mathbb{P}}$ the expectation conditioned on $\mathcal{F}_t$, i.e. $\mathbb{E}_t = \mathbb{E}[\cdot|\mathcal{F}_t]$.

We now consider the case where we draw a player i from a continuum of players. We formalise such a notion assuming a continuously distributed random variable that represents the players. We refer to Figure 3 for a graphical representation of the "drawing" procedure. Given any quantity z^i for player i, we denote by z a random variable, a realisation of which is then given by z^i. The realisation z^i, however, might still be a random variable on some probability space.

A Abatement and trading

For the ease of exposure, we assume that all players have identical abatement costs.[14] Available abatement opportunities are deployed in ascending order of their (short-run) marginal costs of use. So those with the lowest marginal costs are the first ones to be deployed for abatement, and those with the highest marginal costs are the last to be deployed for abatement. Let Π_t represent the marginal cost of the cheapest available means of abatement at time $t \in [0, T]$ and let the process $(\Pi_t)_{t\in[0,T]}$ evolve according to a driftless diffusion:

$$d\Pi_t = G_t(\Pi_t)dW_t, \tag{1}$$

where $(W_t)_{t\in[0,T]}$ is a standard Wiener process. Depending on the relative cost difference between abatement and trading, every player i chooses at time t her instantaneous rate of abatement, α_t^i, and her instantaneous trading rate, β_t^i. By letting α_t^i take negative values, we consider a profitable increase in dirty production. We interpret a positive (negative) β_t^i as selling (buying) a number of $|\beta_t^i|$ permits. The pair (α_t^i, β_t^i) is chosen at time t based on player i's perception of the state of the world $\mathbb{E}_t^{\mathbb{Q}_i} Y_t$; accordingly we assume the process $(\alpha^i, \beta^i) = (\alpha_t^i, \beta_t^i)_{t\in[0,T]}$ to be progressively measurable with respect to $(\mathcal{F}_t^i)_{t\in[0,T]}$.

B Player i's net position

We abstract from the primary market (auction of allowances, EUAs) and concentrate on the secondary market of EUAs. Let i be a random player and $\mathbb{Q}$ be some measure. N_0^i represents the initial endowment of EUAs of player i; ε_T^i represents total emissions of player i over the period $[0, T]$; and φ_T^i represents the total influx of EUAs from the primary market and free allocations for player i over the period $[0, T]$. We define player

[14] This constitutes no limitation on the generality of the model since it can easily be shown that the results hold accordingly if we consider a continuously distributed set of abatement costs.

i's net position at time t under the measure $\mathbb{Q}$ as:

$$X_t^i = N_0^i + \mathbb{E}_t^{\mathbb{Q}}[\varphi_T^i - \varepsilon_T^i] + \int_0^t \alpha_s^i(X_s^i) - \beta_s^i(X_s^i)\, ds.$$

We write:

$$X_t = N_0 + \mathbb{E}_t^{\mathbb{Q}}[\varphi_T - \varepsilon_T] + \int_0^t \alpha_s(X_s) - \beta_s(X_s)\, ds$$

for the random net position yielding the net position X_t^i of any particular player by drawing i.

$$\boxed{X_t} \xrightarrow{\text{Draw Player}} \boxed{X_t^i} \xrightarrow{\text{Draw Path}} \boxed{X_t^i(\omega),\ \omega \in \Omega}$$

Figure 3: Illustration of a game with continuously distributed players. X_t is a random variable representing the level of over or undercompliance. By drawing a particular player i, we obtain a path-valued random variable X_t^i, i.e. a stochastic process. By drawing an elementary event $\omega \in \Omega$, we obtain an actual path of instantaneous over/undercompliance.

C Price formation

Fundamental to our model is the concept of continuously distributed offers to buy and sell EUAs on the market. Consider a market place where participants can offer to buy and sell a quantity of EUA at a specific bid, or asking price, respectively. Figure 4 shows the quantity offered to sell or buy depending on the EUA price (Figure 2, left diagram). Now fix some price level P_t and consider the different order sizes at some point in time. We can then map each order size to the number of occurrences on the market place. A negative number indicates an offer to buy; a positive number indicates an offer to sell. We hereby obtain a representation of the *distribution* of bidder and asked quantities. We refer to the diagram on the right of Figure 4 for a visualization of the number of orders as a function of the order size. Given any order size, represented on the x-axis, the graphs visualize the number of orders with that order size as a corresponding y-value. The blue and red line represent such order size distributions for different EUA price levels. Furthermore we can interpret the hereby obtained distribution as that of a random variable: by drawing a player from our set of participants at any given time, we also obtain the number of EUA she offers to buy or sell at that time on the EUA market.

Notice that if the total number of EUAs offered is not equal to the total number of EUAs requested, the market cannot be cleared: the demand of EUAs is larger (or lower) than the supply of EUAs. By interpreting our distribution as that of a random variable we show that the instantaneous over, or undersupply (for a given price level), is equal to the median of our distribution. Consequently, the EUA price discovery under a market clearing condition has to be such that this median vanishes.

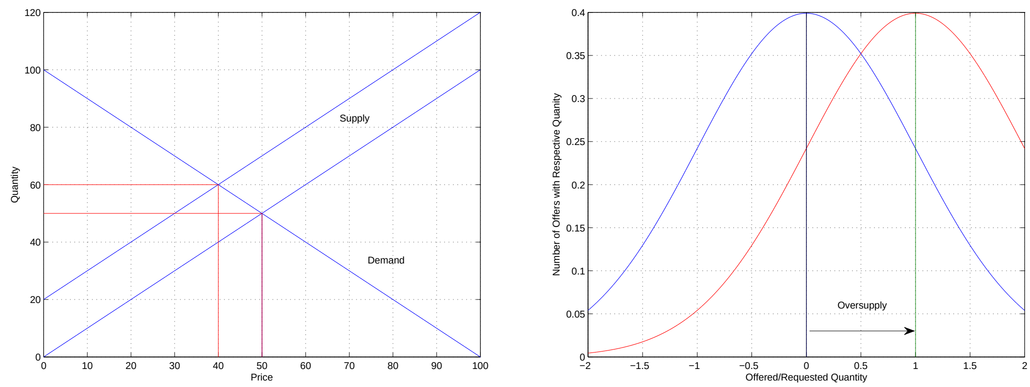


Figure 4: Visualisation of price formation for continuously distributed players. The EUA price adjusts such that supply equals demand (left diagram). Continuous time setting with continuously distributed trading offers (right diagram). The market-wide over/undersupply is given by the median of the distribution of β_t. The EUA price changes instantaneously until the total over/ undersupply vanishes, i.e. the median of β_t equals zero.

As described above, we assume that offers and requests on the EUA market are continuously distributed. In other words we assume that the number of orders on the EUA market at any given time is a continuous function of the order size. In order to explicitly obtain an EUA price, let us now consider a player i with probability measure $\mathbb{Q}^i$. Her perception of instantaneous market over, or undersupply, is given by the median

$$\mathbb{E}_t^{\mathbb{Q}^i} \beta_t(P_t).$$

Hence, player i assumes β_t to be a continuously distributed random variable whose distribution is the distribution of offered- and requested allowance mass. Notice that this is in line with the graph in Figure 3. The distribution of β_t, however, depends on the allowance price P_t. This allows for the price discovery to be accomplished by solving the market clearing equation:

$$\mathbb{E}_t^{\mathbb{Q}^i} \beta_t(P_t) = 0 \tag{2}$$

for P_t. Thus, the EUA price instantaneously adjusts such that the instantaneous supply matches the instantaneous demand. We describe the price discovery via Equation (2) in the following equilibrium model.

D Equilibrium

Let $-i$ denote the players' mass excluding i. We find that, given a particular pair of strategies $(\tilde{\alpha}, \tilde{\beta})$, the optimal stochastic control analysis yields player i's appropriate response to be equal to the pair $(\tilde{\alpha}, \tilde{\beta})$. Thereby, we identify the equilibrium abatement and trading strategies which yields an intuitive equilibrium EUA price dynamics. We define for some net allowance position x as the instantaneous abatement and trading rates:

$$\tilde{\alpha}_t(x) = \frac{-\nu x}{(\nu + \varrho)(T - t)} + \frac{P_t - \Pi_t}{2(\nu + \varrho)}, \tag{3}$$

$$\tilde{\beta}_t(x) = \frac{\varrho x}{(\nu + \varrho)(T - t)} + \frac{P_t - \Pi_t}{2(\nu + \varrho)}. \tag{4}$$

Let us assume that $-i$'s instantaneous trading rate β^{-i} is given by $\beta^{-i} = \tilde{\beta}$. Player i's perception of the EUA price dynamics is based on the price discovery under the (time-independent) measure $\mathbb{Q}^i$. In the eyes of player i, the EUA price adjusts such that the $\mathbb{Q}^i$ (perceived) demand equals the $\mathbb{Q}^i$ (perceived) supply. Recalling that i is an atomistic player and X_t is continuously distributed, we have $\mathbb{E}_t^{\mathbb{Q}^i} X_t = \mathbb{E}_t^{\mathbb{Q}^i} X_t^{-i}$. Thus, the instantaneous market clearing condition at time t implies $\mathbb{E}_t^{\mathbb{Q}^i} \beta^{-i}(X_t^{-i}) = 0$. Consequently, we obtain:

$$P_t = \Pi_t - \frac{2\varrho \, \mathbb{E}_t^{\mathbb{Q}^i} X_t^{-i}}{T - t}. \tag{5}$$

This yields the $\mathbb{Q}^i$-dynamics:

$$dP_t = d\Pi_t + \frac{2\varrho \, d\mathbb{E}_t^{\mathbb{Q}^i} [\varepsilon_T^{-i} - \varphi_T^{-i}]}{T - t}. \tag{6}$$

In order to obtain an arbitrage-free market we assume that both P and Π are $\mathbb{Q}^i$-martingales. Clearly, this holds if, and only if, the second component in Equation (5) is a martingale. This assumption is quite natural: the $\mathbb{Q}^i$-dynamics of $\mathbb{E}^{\mathbb{Q}^i} X_t^{-i}$ represent player i's belief about *the future development of her own beliefs*, which have to be driftless – believing that my belief will change in the future *in a certain direction* makes no sense. For simplicity, we add the assumption

Assumption 1. *Let the measure $\mathbb{Q}^i$ be such that $d\mathbb{E}_t^{\mathbb{Q}^i}[\varepsilon_T^j - \varphi_T^j] = 0$, $j \in \{i, -i\}$.*

In other words, player i does not update her beliefs on the difference $\varepsilon_T^j - \varphi_T^j$.

Player i's optimisation problem. When considering trading on the EUA market we include non-vanishing execution costs. Let $\nu > 0$ be some parameter representing the costs associated with a trading order (e.g. half the bid-ask spread). Thus, the monetary amount paid or received when trading β_t^i at time t corresponds to $\tilde{P}_t = P_t - \nu\beta_t^i$. Atomistic players are price-takers on the EUA market.

Let us begin with the case where the compliance constraint, $\mathbb{E}_t^{\mathbb{Q}^i} X_T = 0$ for all $t \in [0, T]$, is satisfied. Player i seeks to maximize her profit-and-loss (P&L) over the period $[0, T]$. Her P&L from trading over $[0, T]$ is given by P&L $= \int_0^T Z_t^i \, d\tilde{P}_t$, where we denote by Z_t^i the number of permits held by i at time t; i.e. $dZ_t^i = -\beta_t^i \, dt$. This means that at each point in time, the number of EUAs currently held by player i are multiplied by the change in price. This yields the instantaneous profit gained or loss suffered. These instantaneous changes in value are then integrated over $[0, T]$ to obtain the P&L. Then we have:

$$\text{P\&L} = \int_0^T Z_t \, d\tilde{P}_t = Z_T^i \tilde{P}_T - Z_0^i \tilde{P}_0 + \int_0^T \beta_t^i \tilde{P}_t \, dt = Z_T^i \tilde{P}_T - Z_0^i \tilde{P}_0 + \int_0^T \beta_t^i P_t - \nu(\beta_t^i)^2 \, dt.$$

Regarding the abatement strategy, we consider a quadratic influence of the abatement rate α_t^i on the total abatement costs. In other words, we assume that abatement costs increase with successive increase in emission cleanup. It costs a lot more to clean up the last unit of emission than the first. Let $\varrho > 0$ and let player i's optimisation problem consist in finding abatement and trading strategies α^i and β^i, respectively, by maximizing the term:

$$\mathbb{E}_0^{\mathbb{Q}^i}\left[\int_0^T P_t\beta_t^i - \nu(\beta_t^i)^2 - \Pi_t\alpha_t^i - \varrho(\alpha_t^i)^2 \, dt\right],$$

subject to the compliance constraint:

$$\mathbb{E}_t^{\mathbb{Q}^i} X_T^i = 0, \quad \text{for all} \quad t \in [0, T]. \tag{7}$$

Consequently, we define player i's value function on $[0,T) \times \mathbb{R}^3$ as:

$$w^*(t,\pi,\psi,x) = \sup_{(\alpha,\beta)} \mathbb{E}^{\mathbb{Q}^i}\left[\int_t^T P_s^{t,\psi+\pi}\beta_s - \nu\beta_s^2 - \Pi_s^{t,\pi}\alpha_s - \varrho\alpha_s^2 \, ds\right],$$

where ψ denotes the difference $P_t - \Pi_t$, $P_s^{t,\psi+\pi}$ denotes the process satisfying Equation (6) with $P_t^{t,\psi+\pi} = \psi + \pi$ and $\Pi_s^{t,\pi}$ satisfies Equation (1) with $\Pi_t^{t,\pi} = \pi$. Correspondingly, we consider the state process $Y = (Y_t)_{t\in[0,T]}$ with $Y_t = (\Pi_t, \Psi_t, X_t)$.

Lemma 2. *For $\alpha^{-i} = \tilde{\alpha}$ and $\beta^{-i} = \tilde{\beta}$, the Hamilton-Jacobi-Bellman equation for player i's problem of profit maximization is given by:*

$$D_t w + \frac{G_t(\pi)^2}{2} D_\pi^2 w + \frac{1}{4\varrho}(D_x w - \pi)^2 + \frac{1}{4\nu}(\psi + \pi - D_x w)^2 = 0 \tag{8}$$

Furthermore, i's optimal abatement- and trading strategies have to satisfy

$$\alpha_t^i = \frac{D_x w - \Pi_t}{2\varrho} \tag{9}$$

and

$$\beta_t^i = \frac{P_t - \Pi_t}{2\nu} - \frac{\varrho}{\nu}\alpha_t^i. \tag{10}$$

In order to meet the compliance constraint (7) we impose a terminal condition on w:

$$\lim_{t \nearrow T} w(t,x) = \begin{cases} -\infty & : \quad x \neq 0 \\ 0 & : \quad x = 0. \end{cases} \tag{11}$$

Proposition 3. *The Hamilton-Jacobi-Bellman Equation* (8) *with terminal condition* (11) *is solved by*

$$w(t,\pi,\psi,x) = \left(\pi + \frac{\varrho\psi}{\nu+\varrho}\right)x - \frac{\nu\varrho x^2}{(v+\varrho)(T-t)} + \frac{(T-t)\psi^2}{4(\nu+\varrho)}. \tag{12}$$

The abatement and trading strategies $\alpha^{*,i}$ $\beta^{*,i}$ obtained from Equation (12) *using Equation* (9) *and Equation* (10) *are given by*

$$\alpha^{*,i} = \tilde{\alpha}, \quad \beta^{*,i} = \tilde{\beta}.$$

Furthermore $X_t^{*,i}$, given $\alpha^{*,i}$ and $\beta^{*,i}$, satisfies the compliance constraint in Equation (7).

This suggests to consider the *equilibrium strategies*:

$$\left\{\alpha^{i,*}(X_t^i), \beta^{i,*}(X_t^i)\right\}_i = \left\{\tilde{\alpha}(X_t^i), \tilde{\beta}(X_t^i)\right\}_i,$$

which confirm the $\mathbb{Q}^i$-perceived *equilibrium price* process:

$$P_t = \Pi_t - \frac{2\varrho\, \mathbb{E}_t^{\mathbb{Q}^i} X_t}{T-t} = \Pi_t - \frac{2\varrho}{T}\mathbb{E}_t^{\mathbb{Q}^i} X_0$$

with $\mathbb{Q}^i$-dynamics

$$dP_t = d\Pi_t.$$

E Implications

Notice that we obtain a similar decomposition also under the objective measure $\mathbb{P}$:

$$P_t = \Pi_t - \frac{2\varrho\, \mathbb{E}_t^{\mathbb{P}} X_t}{T-t}. \tag{13}$$

However, the EUA price $\mathbb{P}$-dynamics:

$$dP_t = d\Pi_t + \frac{2\varrho\, d\mathbb{E}_t^{\mathbb{P}}[\varepsilon_T - \varphi_T]}{T-t}, \tag{14}$$

has a second component (the distortion term) which is not necessarily a martingale. Using the decomposition in Equation (13) and recalling the definition of the expected under or overcompliance X_t, we obtain the following corollaries:

Corollary 4. *The market has a $\mathbb{P}$-expected zero-net compliance position at time $\tau \in [0, T)$ if and only if at time τ the allowance price equals the marginal cost of abatement.*

The equilibrium price in Equation (13) aligns with the conventional result that the allowance price equals the marginal abatement costs; in other words:

Corollary 5 (Steady State). *For $T \to \infty$, the allowance price P_t converges to the marginal cost of abatement Π_t.*

The decomposition of Equation (13) is quite intuitive: market overcompliance, e.g. overcompliance with respect to the mass of regulated entities, results in EUA prices below the marginal abatement cost. Conversely, market undercompliance results in EUA prices above the marginal abatement cost. The extent to which the EUA price is lower or higher than the marginal abatement cost depends on the market-wide excess imbalance. Therefore, low EUA prices should be regarded as a symptom of a deeper problem rather than the problem itself. We refer to the policy paper, chapter two, for a more comprehensive discussion.

Using the decomposition in Equation (13) and the definition of the net compliance X_t, it follows that the EUA price P_t can be decomposed into the sum of the marginal cost of abatement Π_t and a distortion term as follows:

$$P_t = \Pi_t - \frac{2\varrho}{T-t}\left[N_0 + \mathbb{E}_t^{\mathbb{P}}[\varphi_T - \varepsilon_T] + \mathbb{E}_t^{\mathbb{P}}\left[\int_0^t \alpha_s(X_s) - \beta_s(X_s)\, ds\right]\right]. \tag{15}$$

Equation (15) corresponds to an expanded decomposition of the EUA price in Equation (13) and contains all key components of the EUA price: initial EUA allocation N_0, total EUA allocation φ_T, total emissions ε_T, abatement and trading strategies, respectively. The expanded decomposition in Equation (15) can be used to identify the possible driver of an extremely low permit price. A large N_0 indicates a (potentially excessive) initial allocation of EUAs. With significantly large overallocation, the EUA price can remain relatively low for some time (depending on the level of overallocation). Yet, the initial endowment does not change the price behaviour, as illustrated by Equation (14). The term $\mathbb{E}_t^{\mathbb{P}}[\varphi_T - \varepsilon_T]$ has a interesting interpretation too. Under a linear annual reduction target – as it is implemented in the European Union Emission Trading System (EU ETS) – φ_T is deterministic and, in particular, time- and economy-independent. Instead, $\mathbb{E}_t^{\mathbb{P}}\varepsilon_T$ is economy-dependent. Therefore, the term $d\mathbb{E}_t^{\mathbb{P}}[\varepsilon_T - \varphi_T]$ in the dynamics of Equation (14) is non-vanishing. Hence, an excessive market imbalance determines low EUA prices and, more importantly, a significant distortion in the permit price dynamics.

Excessive Imbalance – Let us focus on the distortion term in Equation (15). Recalling the market clearing condition, $\mathbb{E}_t^{\mathbb{P}}[\beta_s(X_s)] = 0$ for all $s \in [0, T]$, we obtain:

$$P_t = \Pi_t - \frac{2\varrho}{T-t}\left[N_0 + \mathbb{E}_t^{\mathbb{P}}[\varphi_T - \varepsilon_T] + \mathbb{E}_t^{\mathbb{P}}\left[\int_0^t \alpha_s(X_s)\right]\right]. \tag{16}$$

A vanishing distortion term occurs only when the abatement effort, $\mathbb{E}^{\mathbb{P}}\left[\int_0^T \alpha_s(X_s)ds\right]$, equals the offset emissions net of EUAs, $-(N_0 + \mathbb{E}_t^{\mathbb{P}}[\varphi_T - \varepsilon_T])$. Recall that negative α_t corresponds to negative abatement, emissions. When the *required* effort and the *potential* abatement effort are far apart, the EUA price P_t diverges (perhaps significantly) from the marginal abatement cost Π_t. Consider the ratio, $\frac{(N_0+\mathbb{E}_t^{\mathbb{P}}[\varphi_T-\varepsilon_T])}{\mathbb{E}^{\mathbb{P}}\left[\int_0^T \alpha_s(X_s)ds\right]}$. An extremely large ratio indicates that the market is excessively imbalanced. This occurs when (i) the *required* offset effort is large and negative, and the (negative) abatement opportunities are very limited; (ii) the *required* offset effort is large and positive, and the (positive) abatement opportunities are very limited. In the first case the EUA price is lower than the marginal abatement cost; in the second case it is larger than the marginal abatement cost.

Below we suggest a transparent and simple, rules-based programme designed to make the EU ETS responsive, i.e. to respond to excessive market imbalance scenarios.

F Policy suggestion

We propose a double trigger intervention policy. The first trigger indicates the condition under which there is an intervention and is based on an observed price-drift rule. The second trigger indicates the magnitude of the intervention and is based on a quantity rule derived from Equation (13). The intervention algorithm works as follows: at certain revision dates $\{\tau_k\}_{k=1,...,n}$, the empirical price drifts μ_a and μ_b over the past periods $[\tau_k - a, \tau_k)$ and $[\tau_k-(a+b), \tau_k-a)$ are estimated using historical daily rate of returns. The length of the time windows, a and b, should be chosen with the trade-off between *timely action* and potential *manipulation* in mind. We suggest the following time windows: 6-12 months for a and 24 months for b. Using the decomposition in Equation (14), a significant change in the price trend, e.g. μ_a extremely larger or smaller than μ_b, indicates a significant $d\mathbb{E}_t^{\mathbb{P}}[\varepsilon_T]$. By abating and trading, players respond to variations in $\mathbb{E}_t^{\mathbb{P}}[\varepsilon_T]$. However, when the required offset effort, relative to the potential abatement and trading opportunities, are excessive, the EUA price will deviate from its steady state. Hence, we have an excess market imbalance that requires regulator's intervention. This is the first trigger. The regulator's intervention operates via φ_T : the availability of (future) EUAs will be increased or reduced, depending on the sign of the imbalance; positive indicates oversupply, and negative indicates undersupply. In particular, using the decomposition in Equation (13), the instantaneous over, or undersupply, X_t determines the intervention magnitude under the objective $|P_{\tau_i} - \Pi_{\tau_i}| \to \min$ for $i = 1, ..., n$ and $|dP_t - d\Pi_t| \to \min$

for $t \in [0, T]$. This is the second, volume-based trigger.[15]

The mechanism described above induces an auto-correction effect. Suppose that, before an EUA auction revision date τ, there has been a price trend significantly lower than the price trend in the preceding two years. Anticipating the intervention, regulated entities' perceived probability of the regulator's intervention increases. Consider player i. She will revise her expectations about future allocation, $\mathbb{E}^{\mathbb{Q}^i}[\varphi_T]$. The more transparent and simple the intervention rules, the more immediate and exact the revised expectations about the future EUA allocation. As indicated in Equation (6), by revising the future EUA allocations the equilibrium price dynamics changes. Consequently, as indicated in Equation (3) and Equation (4), player i will adjust her trading and abatement strategies. Depending on the sign of the intervention, player i may decide to abate more and trade less, or vice versa. It should be noted that the auto-correction reduces the magnitude of the required intervention at τ. In fact, the more transparent and simple the rules are about *if* to intervene and *the level* of intervention, the lower the regulator's intervention effort.

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