Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

FAKULTÄT
FÜR WIRTSCHAFTS- UND SOZIALWISSENSCHAFTEN

Consulting the chrystal ball: Firm's foresight and a cap-and-trade scheme with endogenous supply adjustments

Maximilian Willner

WiSo-HH Working Paper Series
Working Paper No. 46
August 2018

WiSo-HH Working Paper Series
Working Paper No. 46
August 2018

Consulting the chrystal ball: Firm’s foresight and a cap-and-trade scheme with endogenous supply adjustments

ISSN 2196-8128

Font used: „TheSans UHH“ / LucasFonts

Die Working Paper Series bieten Forscherinnen und Forschern, die an Projekten in Federführung oder mit der Beteiligung der Fakultät für Wirtschafts- und Sozialwissenschaften der Uni-versität Hamburg tätig sind, die Möglichkeit zur digitalen Publikation ihrer Forschungser-gebnisse. Die Reihe erscheint in unregelmäßiger Reihenfolge.

Jede Nummer erscheint in digitaler Version unter
https://www.wiso.uni-hamburg.de/de/forschung/working-paper-series/

Kontakt:
WiSo-Forschungslabor
Von-Melle-Park 5
20146 Hamburg
E-Mail: experiments@wiso.uni-hamburg.de
Web: http://www.wiso.uni-hamburg.de/forschung/forschungslabor/home/

Consulting the chrystal ball:
Firm's foresight and a cap-and-trade scheme with endogenous supply adjustments

Maximilian Willner [*]

August 15, 2018

Abstract

The latest reform of the European Emissions Trading System (EU ETS) will set in motion range of changes to the scheme including the Market Stability Reserve (MSR). It will postpone the issue date of allowances as a function of the unused allwances in circulation, i.e. the so-called 'surplus', and cancel allowances as a function of the reserve size from 2023 onwards. Both aspects of the MSR have implications for market outcomes which in turn depend on the nature of foresight experienced by market participants. We distinguish between perfect, limited and imperfect foresight and analyze a perfectly competitive allowance market by a partial equilibrium model in discrete time. Our investigation yields that the current design put in place by the reform is only sensible if two market failures are taken into account: excessive supply by the regulator and regulated entities not experiencing perfect foresight.

Keywords: Market stability reserve; cap-and-trade; EU ETS reform; foresight; myopia; market failure

JEL codes: D21; D47; Q58; Q54

[*]University of Hamburg, Department of Socioeconomics, maximilian.willner@wiso.uni-hamburg.de

1 Introduction

Within the plentitude of policy instruments at disposal to facilitate a transition towards a low-carbon economy, the European Union (EU) chose permit trading to be at the heart of its climate change mitigation policies (Convery, 2009). Since 2005, the European Emissions Trading System (EU ETS) has put a price on carbon and will soon enter its fourth trading period (Phase 4, 2021-2030). However, the price for one ton of CO_2-equivalent[1] declined from about 30€ in 2008 to below 5€ by the summer of 2017.

From the point of view of the scientific community, the EU and major industry representatives, a price far below the social cost of carbon endangers the attainment of mitigation goals and poses a heavy burden on societies in the future as climate damages might rise intolerably (Tol, 2009; Nordhaus, 2014; Knopf et al., 2014; Venmans, 2016; European Parliament and Council, 2018; Gerlagh & Liski, 2018). Prices in line with the climate targets laid out in the Paris Agreement of 2015 should be around \$40-\$80 (35€-69€) by 2020 and \$50 - \$100 (43€ - 86€)[2] by 2030 as proposed by a commission on carbon pricing led by Joseph Stiglitz and Nicholas Stern (High-Level Commission on Carbon Prices, 2017).

In that vein, the EU ETS is considered to give too little incentives to regulated entities to invest in low-carbon technologies in a sufficient and timely manner. Recent data shows that e.g. Germany is bound to miss its carbon reduction targets for 2020 by about 100 million tons of CO_2-equivalent (BMU, 2018). The European Commission (EC) considers the amount of allowances in circulation in the EU ETS - the so-called 'surplus' or aggregate bank - to be the reason for low prices. In broader terms, the 1.65 billion allowances held by market participants and intermediaries at the end of 2017 in combination with yet to be allocated quantities are thought to represent an excessive supply (European Commission, 2018). In order to improve the system and bolstering the price signal, the EU ETS will undergo reform. Beside other measures, the Market Stability Reserve (MSR) will start operating in 2019 (European Parliament and Council, 2018). The MSR will alter the yearly supply schedule of the EU ETS based on the number of allowances in circulation at the end of the previous year. It will take in allowances, store them and release them depending on whether the aggregate bank is above or below certain thresholds.[3] This we call the dynamic backloading aspect of the MSR.

Furthermore, by 2023, should the amount of allowances stored exceed the amount of auctioned allowances of the previous year, the excess amount will be canceled from the reserve. Importantly, the amount of allowances in the MSR by then will depend on how much will have been taken in before, which in turn depends on the banking behavior of market participants, i.e. it is determined endogenously. Cancellations will go on as long as the reserve does not inject more allowances than the amount of auctioned allowances declines by fixed yearly cap reductions, i.e. the linear reduction factor (LRF, see also Perino (2018)). This we call the endogenous cancellation aspect of the MSR.

[1] Measured at prices of futures with yearly roll-over in December.

[2] Exchange rates as of 7th August 2018.

[3] See Perino & Willner (2016) and Perino (2018) for a more detailed description.

The idea behind the MSR is to increase short-term scarcity and persuade market participants to draw down their stores of allowances. As intertemporal arbitrage does not as such lead to inefficiency, policies targeting the aggregate bank and not the primary allocation mechanism implicitly insinuate a market failure to be present (Schleich et al., 2006; Schopp & Neuhoff, 2013; Koch et al., 2014). A correctly calibrated cap-and-trade scheme with adequate supply and perfectly foreward looking market participants would result in the appropriate price and aggregate bank in terms of internalization of the climate externality. Multiple reasons for this not being the case in the EU ETS have been investigated in the past, such as political uncertainty (Salant, 2016; Koch et al., 2016), risk aversion (Kollenberg & Taschini, 2016) and reasons for excessive supply due to offsets, overlapping policies or demand shocks (Böhringer et al., 2009; Koch et al., 2014; Hintermann et al., 2015; Jarke & Perino, 2017). Depending on the diagnosis, proposals like a discretionary carbon central bank (De Perthuis et al., 2011; Grosjean et al., 2016), a more flexible reserve mechanism (Kollenberg & Taschini, 2016; Gerlagh & Heijmans, 2018) or price containing mechanisms such as price floors or corridors have been suggested (Wood & Jotzo, 2011; Edenhofer et al., 2017; Newbery et al., 2018).

Current low prices could as well stem from impaired foresight of market participants, leading to a price "hockey stick effect", i.e. lower than optimal prices in the short term and higher than optimal prices in the long term (Holt & Shobe, 2016; Edenhofer et al., 2017; Fuss et al., 2018). Market participants might not take into account the full scope of future scarcity. Put differently, firms' foresight in the absence of uncertainty might deviate from the common definition of perfect foresight (Muth, 1961; Bray, 1987). We subsume expressions such as myopia, short-sightedness or impatience under impaired foresight (Perino & Willner, 2017b).

In this paper, we investigate market outcomes in a cap-and-trade scheme with a reserve mechanism featuring dynamic backloading and endogenous cancellations. To account for different assumptions about firms's behavior, we define three scenarios of foresight: perfect, limited and imperfect foresight.

Depending on the scenario, the reserve's impacts on prices and total abatement costs differ. Our choice of scenarios covers two different aspects of impaired foresight. While limited foresight cuts the scope of a firm's planning horizon short, i.e. only the near future matters for decisions with total neglect of all that follows, imperfect foresight appeals to a firm's inability to correctly understand and process future market conditions. In the latter case while not neglecting the future, the firm resorts to heuristics, i.e. in this paper the extrapolation of current conditions. Importantly, we focus solely on firms' incapacity to exhibit perfect foresight and refrain from modeling exogenous shocks, political uncertainty or regulatory discretion.

This contribution is relevant for the literature concerning cap-and-trade scheme design and firm behavior and adds to the discussion of climate policy instrument choice. Furhtermore, the alterations of the model to accomodate different scenarios of foresight add to the endeavor of producing easily comprehensible yet meaningful results.

In section 2 of the paper, we discuss the implications of the different scenarios for a cap-and-trade scheme in a two period partial equilibrium model of a perfectly competitive allowance market. First, we establish a perfect foresight reference case. Second, we define limited and imperfect foresight and explain which disruptions are caused by misperceptions of future scarcity. Following in section 3, we isolate the dynamic backloading aspect. Only in very restricted cases does the implementation of the reserve improve cost-effectiveness of the system and can correct for limited or imperfect foresight. Next, section 4 is dedicated to a study of endogenous cancellations. We discuss its impacts under the different scenarios of foresight and point out the consequences for goals set out by the regulator when seen together with dynamic backloading. Section 5 concludes.

2 The model of market behavior

We consider a cap-and-trade scheme for carbon emissions which is operational for two trading periods of equal length. The scheme starts at $t = 0$, moves to the second period at $t = 1$ and ends at $t = 2$. Choosing this set-up allows us to later investigate different policy regimes of the scheme where second period outcomes depend on decisions made in period 1 without overextending the analysis. Typically, a period would span 5-10 years (Perino & Willner, 2017a). Each period, the regulator issues S_t allowances in line with an overall carbon budget steering the decarbonization of the regulated sector(s). The legal framework setting up the scheme is fixed prior to $t = 0$ and is not subject to change. Hence, an *objective* source of political uncertainty as examined by e.g. Salant (2016) and Koch et al. (2016) is not considered here. However the paper will allow for doubt about the longevity of the scheme, available yet misperceived information or a limited planning horizon as a source of *subjective* uncertainty experienced by market participants.
We start by considering the reference case of a competitive market for emission allowances populated by a continuum of polluting firms with mass one who minimize their present value abatement costs and exhibit perfect foresight. The latter means that while still being price-takers, firms foresee future allocations issued by the regulator, correctly predict overall scarcity in both periods, exhibit full trust in the rules set out priorly and behave dynamically consistent.

2.1 The reference case with perfect foresight

Firm i faces a standard optimization problem in discrete time. Abatement, $\alpha_{i,t}$, is equal to constant counter-factual business-as-usual emissions denoted by $u_i > 0$ less intermittent emissions denoted by $e_{i,t} \in [0, u_i]$. The cost function of abatement $C(\alpha_{i,t})$ is convex and assumed twice continuously differentiable with $\partial C(\alpha_{i,t})/\partial \alpha_{i,t} > 0$ and $\partial^2 C(\alpha_{i,t})/\partial \alpha_{i,t}^2 > 0$. As the trading scheme demands full coverage of firms' emissions in each period and attaches a prohibitively high monetary penalty to non-compliance, a binding cap is assured. Between periods, firms are allowed to bank allowances but not to borrow, i.e. $b_{i,t} \geq 0$, which is in line with related literature and real world design choices (Schennach, 2000; Perino & Willner, 2016; Kollenberg & Taschini, 2018). To cover its emissions, a firm can either use an inital stock of banked allowances accumulated from the past, $b_{0,i} \geq 0$, or buy allowances from other participants or auctions.[4] The amount of allowances traded in the market and bought at auctions at price $P_t \geq 0$ is denoted by $x_{i,t}$, with a negative sign indicating a net-sale and a positive sign indicating a net-purchase of allowances. This amount will be greater or equal to emissions less the amount of banked allowances as it would otherwise lead to non-compliance. If the firm purchases (sells) more (less) allowances than the difference between emissions and previously banked allowances, it transfers allowances to the next period, i.e. $b_{1,i} > 0$. Furthermore, there is an upper limit to purchases, because each period the supply of allowances can not exceed the amount offered at auctions and the quantities held by other market participants, i.e. $x_{t,i} \leq S_t + B_{t-1} - b_{t-1,i}$. In aggregate[5], net purchases equal the number of auctioned allowances. Firms discount the second trading period by the market interest rate $r > 0$. A firm's optimization problem for emission quantities and market transactions then states:

$$\begin{aligned} & min_{e_{t,i},x_{t,i}} \sum_{t=0}^{2} C(e_{t,i}, x_{t,i}) \\ s.t.: \quad & x_{1,i} \geq e_{1,i} - b_{0,i} \\ & x_{1,i} \leq S_1 + B_0 - b_{0,i} \\ & b_{1,i} = x_{1,i} + b_{0,1} - e_{1,i} \\ & 0 \leq e_{t,i} \leq u_i \end{aligned}$$

For the remainder of the paper, we choose a quadratic cost function:

$$C(e_{t,i}, x_{t,i}) = \frac{c}{2(1+r)^{t-1}} \left[(u_i - e_{t,i}) + P_t x_{t,i} \right]$$

Heeding the constraints on the state ($b_{1,i}$) and the two control variables ($e_{t,i}$, $x_{t,i}$), firms' optimization results in the optimal choice of emissions for each period with a star denoting optimality.

$$e^*_{t,i} = u_i - \frac{P_t}{c} \tag{1}$$

Keeping in mind that borrowing is not allowed, in case the firm engages in intertemporal

[4] We opt for full auctioning as this serves the purpose of simplicity when looking at overall costs. However, check Perman et al. (2011) (pp. 200-208), Cramton & Kerr (2002), Neuhoff et al. (2006) and Hahn & Stavins (2011) for further elaboration. Including an initial amount of banked allowances reflects the existence of allowances in circulation in the EU ETS and will serve its purpose when looking at the reserve mechanism later on.

[5] We denote aggregate values by capital letters. The following example shows our definition of aggregate values where i serves as a weight. Let y_i be an integratable firm parameter: $y_i := 2iY$ and then $\int_0^1 y_i \, \mathrm{d}i = Y$.

arbitrage and emits a positive amount, i.e. it keeps allowances in a private bank from period 1 to period 2, it does so only when facing a price rising at the interest rate. Should it rise faster, there will be zero emissions and full banking. If the price rises less than the interest rate, it is not optimal to keep allowances for later use and $b_{1,i} = 0$. This is a well established result in the literature on emission trading and banking for competitive markets (Cronshaw & Kruse, 1996; Rubin, 1996; Salant, 2016).[6]

With a declining cap, firms will only bank allowances if the relative percentage point increase in scarcity between one period and the next is greater than the market interest rate measured in percentage points. In this model, a declining cap is incorporated by a fixed amount a by which the number of allowances auctioned in period 2 (S_2) is smaller than in period 1, i.e. $S_1 = S$ and $S_2 = S - a$, with $U > S > 0$. Here, the knowledge of future auction quantities is a feature of perfect foresight of the firm. It stems directly from the full understanding of the system's supply schedule, which leads firms to correctly predict future prices.[7] Given all other parameters, it is possible to define a critical value for the market interest rate, called $\bar{r}_{PF}$[8], at which all firms are indifferent between banking and not banking allowances given overall scarcity. This is the case when the maximum relative increase in scarcity of allowances and accompanying cost from period 1 to period 2 (from $S_1 = S + B_0$ to $S_2 = S - a$) is equal to the return on an alternative investment devaluated by the market interest rate. Should it be larger, it makes sense to bank allowances to use them later and should it be lower, firms would like to borrow but cannot. For perfect foresight, the value of the critical intake rate is given by:

$$\bar{r}_{PF} = \frac{B_0 + a}{U - B_0 - S}$$

Hence, at least one firm will engage in banking when $r < \bar{r}_{PF}$, leading to $B_1 > 0$. Throughout the paper, we implicitly assume a market interest rate below the relevant critical value, thus focusing on sets of parameters for which banking occurs in equilibrium in abscense of a policy intervention. We limit the analysis in this fashion because in case there is no incentive to bank, the results of optimization would be trivially the same in all three foresight scenarios discussed below. Moreover, since our conception is guided by the EU ETS, the presence of an aggregate bank is a prominent feature to mimic.

2.2 The Market Equilibrium

When looking at the market for allowances, we need to choose parameters assuring overall scarcity so that the price for allowances will not be zero in both periods, i.e. there is a need to undertake some abatement. Hence, with perfect foresight and no reserve policy we have $S_1 = S$ and $S_2 = S - a$ and $2U > 2S + B_0 - a$. We use the results from optimization at the firm level (Equation 1) to derive the market price for allowances.

[6] See Chen & Tanaka (2018) for a recent contribution on imperfect competition.

[7] For a more detailed derivation, consult Appendix **??**.

[8] The subscript describes the foresight scenario. Subscript notation: Perfect foresight (PF), limited foresight (LF), imperfect foresight (IF). For expressions valid for all three scenarios, we use m.

$$\int_0^1 e_{1,i}^* + e_{2,i}^* \, \mathrm{d}i = \int_0^1 b_{0,i} + x_{1,i} + x_{2,i} \, \mathrm{d}i$$
$$\Leftrightarrow$$
$$\int_0^1 2u_i - \frac{P_1 + P_2}{c} \, \mathrm{d}i = B_0 + S_1 + S_2 \tag{2}$$
$$\Leftrightarrow$$
$$2U + \frac{P_1 + P_2}{c} = B_0 + 2S - a$$

With banking (subscript b), i.e. $r < \bar{r}_{PF}$, prices rise at the interest rate, hence $P_2 = (1+r)P_1$:

$$P_{1,b,PF} = \frac{c}{2+r}(2U - 2S - B_0 + a)$$
$$P_{2,b,PF} = \frac{(1+r)c}{2+r}(2U - 2S - B_0 + a)$$

Without banking (subscript nb), i.e. $r \geq \bar{r}_{PF}$, prices rise less than at the interest rate, hence $P_2 = (1+r)(P_1 - \lambda)$:[9]

$$P_{1,nb,PF} = c(U - S - B_0)$$
$$P_{2,nb,PF} = c(U - S + a)$$

With equilibrium prices and quantities at hand, it is now possible to calculate the present value of total abatement costs (TACs) of the policy regime. TACs represent the gross financial burden on society to achieve the policy-prescribed reduction target. In standard welfare analysis the environmental benefits of emission reductions are taken into account, too, but since we consider a cost-effectiveness framework and do not alter the underlying allowance quantities for each scenario of foresight, studying costs only does not lead to a loss of generality.[10] Further, we abstract from revenue redistribution and rebates by the regulator because it would add a layer of complexity not necessary to investigate the partial equilibrium results of this model.

$$\begin{aligned} \text{TACs}_m &= \int_0^1 C_m(e_{t,i,m}) \, \mathrm{d}i \\ &= \frac{2c}{3}[(U - E_{1,m})^2 + \frac{(U - E_{2,m})^2}{1+r}] \end{aligned}$$

Next we turn to a specification of different foresight scenarios and take a look at associated costs in the abscence of a reserve policy.

[9] Consult Appendix **??** for more details.

[10] This changes when looking at endogenous cancellations. For that matter, we will revisit this topic later on.

2.3 Foresight scenarios

From the deliberations above it is evident that banking allowances for future use is a typical feature of optimization under perfect foresight. The mere existence of a privately held bank, e.g. the so-called 'surplus' in the EU ETS, should therefore be of no concern for the cost-effective attainment of the carbon reduction goal manifest in the overall cap. In fact, it is a result of the incorporation of future scarcity into present day emission decisions. However, it is doubtful whether firms possess the necessary clarity and foresight vis-à-vis market processes and future allocations or are able to appropriatly incorporate all available information into their decision-making process.

Prices for a ton of CO_2-equivalent that are considered too low to drive low-carbon technological change – which has been said to be the case over long periods of time in the EU ETS – might thus stem from misperceptions about future scarcity due to e.g. cognitive constraints, short-sightedness or other sources of impaired foresight (Koch et al., 2014; Hintermann et al., 2015; Salant, 2016; Edenhofer et al., 2017; Perino & Willner, 2017a).[11]

Nevertheless it is not logically consistent to argue that a high number of banked allowances reflects an underestimation of long-run scarcity. If market participants misperceive future scarcity out of whatever reasons, they would deplete their banks and emit more, thus leading to depressed prices now and higher prices in the future. While the symptom of low prices could then occur due to impaired foresight, a large aggregate private bank is not the root of the problem. As explained above, the greater the increase in relative scarcity between period 1 and period 2, the higher the incentive to bank for the future. It should then be a goal to decrease (increase) emissions (abatement) and increase incentives to bank allowances for later. Looking at the current situation in the EU ETS, if future scarcity was insufficiently anticipated, the surplus would be too low and not too high. If it was correctly anticipated, prices that are 'too low' to stipulate low-carbon technology investment then relate to the overall supply being insufficiently tuned to the internalization of the climate externality. A problem that could be solved by simply reducing the amount of yet to be allocated allowances directly.

Clearly, the appropriate response of the regulator to the perceived problem of low prices crucially depends on firms' foresight. As a misperception of reality, we can discern two forms deviant from perfect foresight: limited and imperfect foresight.

Limited foresight

Limited foresight describes a situation where participants are perfectly informed about market conditions in the near future, i.e. period 1 in the model, but do not form expectations beyond that, i.e. period 2. Restricting the time-frame of optimization to one period could have different reasons such as limited managerial planning horizons, fundamental doubt about the existence of the regulatory framework after period 1, prohibitively high costs of forecasting or extreme

[11] The EU does not express this finding quite like this but relates to a robust investment signal for low-carbon technologies when giving reasons for reform and allocation interventions (European Commission, 2014). A hint at the assumed link between prices and allocations is given e.g. in the EU's handbook on the trading system on page 92 (DG Climate Action, 2015).

impatience in the form of the firms' rate of time preference high above the social one. In this setting, the optimization at hand reduces to a two-stage problem. Leaving a bequest in form of a privately held bank at the end of period 1 is thus not optimal. Accordingly, the outcome for prices and TACs is the same as under perfect foresight for all values of $r \geq \bar{r}_{PF}$,[12]

$$
\begin{aligned}
&\text{stage 1} \\
&\qquad min_{e_{t,i,LF},x_{t,i,LF}} C(e_{1,i,LF}, x_{1,i,LF}) \\
&s.t.: \quad x_{1,i,LF} = e_{1,i,LF} - b_{0,i} \\
&\qquad 0 \leq e_{1,i,LF} \leq u_i \\
&\text{with} \quad E_1 = B_0 + S_1 \\
&\text{stage 2} \\
&\qquad min_{e_{t,i,LF},x_{t,i,LF}} C(e_{2,i,LF}, x_{2,i,LF}) \\
&s.t.: \quad x_{2,i,LF} = e_{2,i,LF} \\
&\qquad 0 \leq e_{2,i,LF} \leq u_i \\
&\text{with} \quad E_2 = S_2
\end{aligned}
$$

In contrast to the banking case under perfect foresight, prices in both periods are independent for all r:

$$
\begin{aligned}
P_{1,LF} &= c(U - B_0 - S) \\
P_{2,LF} &= c(U - S + a)
\end{aligned}
$$

Imperfect foresight

Turning to imperfect foresight, firms take both periods into consideration for cost minimization. In contrast to perfect foresight, they do not posess all relevant information about market conditions in period 2 but need to form an expectation based on observations made in period 1, i.e. they are correctly informed for period 1 but not period 2. Multiple determinants could serve for a function of price expectations of the firms, but for the purpose of this paper we resort to a simplified mechanism observed in asset pricing: the extrapolation of current conditions (Hommes et al., 2004; Heemeijer et al., 2009; Barberis et al., 2015). Firms act as if current market conditions were stable over both periods and expect prices to react accordingly. Again, we model this as a two stage optimization problem, where firms commit to a level of emissions and market transactions vis-à-vis period 1 and expected period 2 conditions and can then adjust their plan for period 2 once it arrives and they learn all necessary information of the market environment. This approach picks up the argument concerning dynamic inconsist behaviour in the context of the EU ETS put forward by Perino & Willner (2017b).

From the firms' perspective, the optimal behavior does not change in comparison to the reference case, i.e. equation 1 still holds for $e_{1,i}$ and $e_{2,i}$. What changes are price expectations based on

[12] We would get the same result if firms expected an abundance of allowances in the future and only bring into focus one period.

the different perception of future scarcity which we reflect by adapting the market equilibrium conditions accordingly. For the first stage optimization, we express period 2 supply by $\tilde{S_2} = S_1$ which alters the market equilibrium. Observe that $\tilde{S_2}$ now does not include the reduction of the cap, a.[13]

$$\begin{aligned}
&\text{stage 1} \\
&\qquad min_{e_{t,i,IF},x_{t,i,IF}} C(e_{t,i,IF}, x_{t,i,IF}) \\
&s.t.: \quad x_{1,i,IF} \geq e_{1,i,IF} - b_{0,i} \\
&\qquad x_{1,i,IF} \leq S_1 + B_0 - b_{0,i} \\
&\qquad 0 \leq e_{1,i,IF} \leq u_i \\
&\text{with} \quad E_1 + E_2 = B_0 + S_1 + \tilde{S_2};\ \tilde{S_2} = S_1
\end{aligned}$$

$$\begin{aligned}
&\text{stage 2} \\
&\qquad min_{e_{t,i,IF},x_{t,i,IF}} C(e_{2,i,IF}, x_{2,i,IF}) \\
&s.t.: \quad x_{2,i,IF} = e_{2,i,IF} \\
&\qquad 0 \leq e_{2,i,IF} \leq u_i \\
&\text{with} \quad E_2 = B_1 + S_2
\end{aligned}$$

The prices realizing in this scenario are thus:

$$P_{1,IF} = \frac{c}{2+r}(2U - B_0 - 2S)$$
$$P_{2,IF} = c(U - S - B_{1,IF} + a)$$

Comparison and discussion

We can now juxtapose the three different scenarios by plotting TACs and prices in the abscence of a reserve policy (see Figures 1 and 2).[14]

[13] We again focus on the banking case with $r < \bar{r}_{IF}$. In fact, if $r \geq \bar{r}_{PF}$, i.e. in a world with $B_{1,PF} = 0$, all three scenarios would create the same outcome. See Annex **??** for more details.

[14] The parameters used for the graphical representation throughout the paper can be found in Annex **??** or if varying they are indicated in the text.

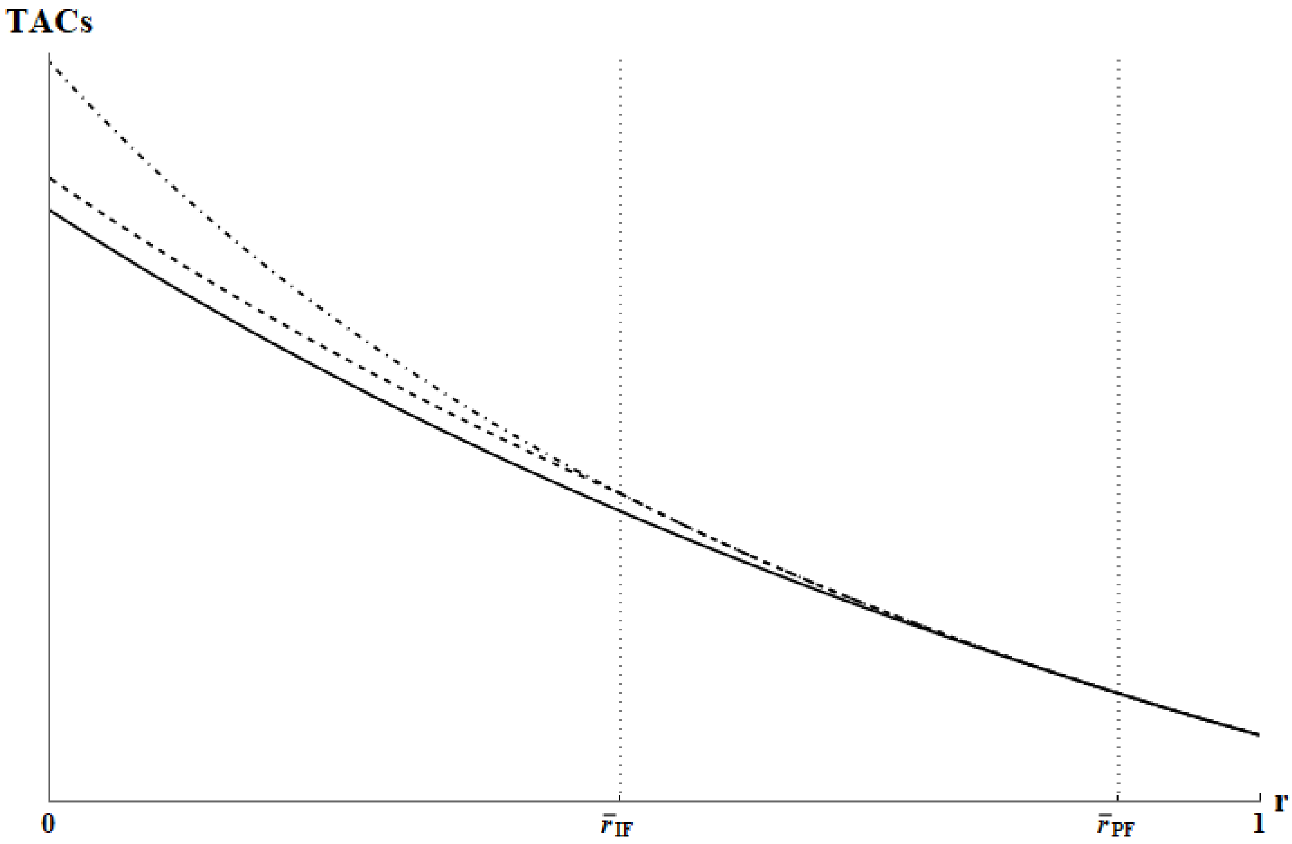

Figure 1: TACs are presented for different values of r. The solid line shows TACs under perfect, the dash-dotted line under limited and the dashed line under imperfect foresight. Due to the underestimation of future scarcity, $\bar{r}_{PF} > \bar{r}_{IF}$, here represented by dotted gridlines. For this graph, we use $B_0 = 8$ and $a = 7$ to guarantee $\bar{r}_{PF} < 1$.

For values of $r < \bar{r}_{IF}$, limited foresight leads to higher TACs than under both imperfect and perfect foresight, as period 2 is completely neglected and firms do not bank. While they bank under imperfect foresight, they do so less than optimally due to the neglection of the declining cap. If $\bar{r}_{IF} \leq r < \bar{r}_{PF}$, TACs under imperfect and limited foresight are identical as well as higher than under perfect foresight as banking ceases in the former scenarios and not in the latter. For values of $r \geq \bar{r}_{PF}$, TACs are equal to limited foresight in the other two scenarios as there are no incentives to bank allowances in either one of them.[15] The declining cap manifest in $-a$ in period 2 increases the difference between imperfect and perfect foresight and consequently also between perfect and limited foresight, since:

$$\frac{\partial(\text{TCA}_{\text{IF}} - \text{TCA}_{\text{PF}})}{\partial a} = \frac{ac}{(1+r)(2+r)} > 0$$

.

Misperceiving future scarcity under both limited and imperfect foresight leads to lower allowance prices in period 1 and higher prices in period 2 when compared to the market under perfect foresight. The result is a greater interperiod appreciation of allowance prices.

[15] See Annex ?? for clarification.

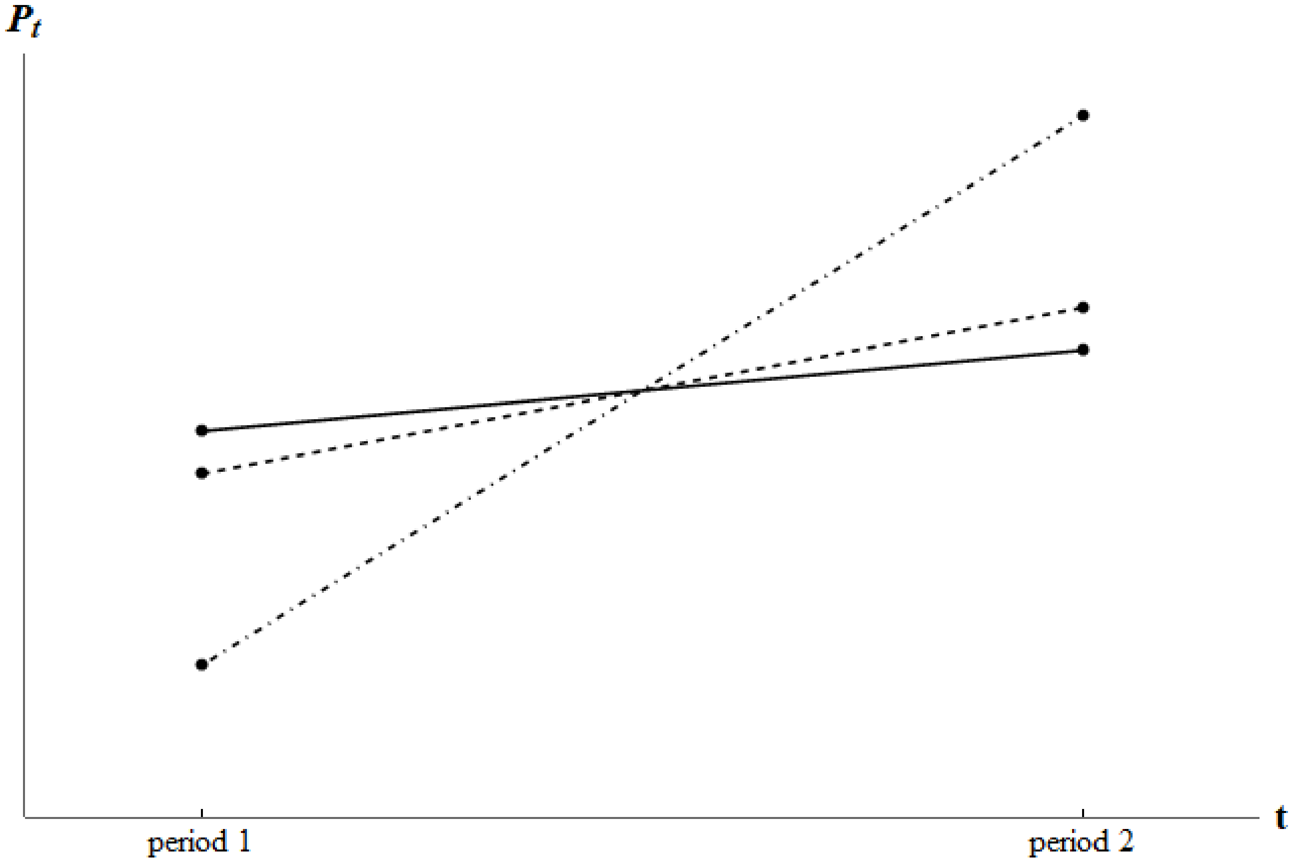

Figure 2: The solid line connects current value prices under perfect, the dot-dashed line under limited and the dashed line under imperfect foresight.

For the current discussion about reforming the EU ETS, the so-called 'hockey-stick-effect'[16] (Borenstein et al., 2015; Edenhofer et al., 2017) is an argument to pass legislation to increase current prices. The sooner regulated firms are confronted with higher costs of emissions, their incentives to embark on a path of technological renewal and to invest into low-carbon alternatives should rise.[17] The dangers of a high-carbon technlogical lock-in and ultimately the failure to achieve mitigation targets loom in low short-term prices in case of impaired foresight (Unruh, 2000; Kalkuhl et al., 2012; Erickson et al., 2015; Perino & Willner, 2017b). At the heart of the upcoming reform is a reserve mechanism with endogenously determined cancellations whose impact crucially depends on the scenario of foresight.

3 The reserve mechanism

3.1 Setup and impact without cancellations

We investigate a reserve mechanism modeled loosely after the MSR to be introduced to the EU ETS in 2019, which will have a direct impact on the supply of allowances. This impact depends on the previous period's aggregate private bank. If the aggregate bank is larger than

[16] Low and slowly rising current prices and quickly exploding future prices form a curve that looks like a hockey stick from handle to tip.

[17] This need not be a monotonic relationship as shown by Perino & Requate (2012).

an upper threshold, $\overline{B}$, the reserve stores allowances that would otherwise be auctioned off and thus reduces supply in that period. The amount of allowances taken in is equal to the aggregate bank times the intake rate, ρB_{t-1} with $\rho \in [0, 1]$. A fix amount of I allowances gets injected if the aggregate bank is smaller than a lower threshold, $\underline{B}$, with $I = \min[\rho(B_0+B_1); \bar{I}]\ with\ \bar{I} > 0$. Should it be in between the threshold values, i.e. $\overline{B} \leq B_{t-1} \leq \underline{B}$, the reserve remains idle. This is summarized in Table 1.

Table 1: The reserve's reaction to aggregate private bank levels (bold)

B_{t-1}	$> \overline{B}$	$\leq \overline{B} \wedge \geq \underline{B}$	$< \underline{B} \wedge \geq 0$
S_t	$S-(t-1)a \boldsymbol{-\rho B_{t-1}}$	$S-(t-1)a$	$S-(t-1)a \boldsymbol{+I}$

For the remainder of this paper, we assume $B_0 > \overline{B}$ to focus on a reserve mechanism that *reduces* auctioned quantities in period 1, i.e. allowance supply is initially cut by $-\rho B_0$. The reason for this decision is that the EU ETS exhibits such a situation, which makes the reserve meaningful to start with. The MSR will take in 265 million allowances in the first 8 months of 2019 (European Commission, 2018). Allowances that are stored in the reserve are fed back to the market within period 2. This results in a net-effect of $+\rho B_0$ in period 2, irrespective of the size of B_1. For now we focus on the dynamic backloading aspect of the reserve to isolate its effects.

3.2 Perfect foresight

For now, it is only the intake rate, ρ, which will determine the reserve's impact on the system. If $\rho = 0$, the policy scenario is identical to the reference scenario without a reserve policy in place. If $\rho > 0$, the reserve creates additional scarcity in period 1 which has an impact on the banking behavior of firms. Given $r < \bar{r}_{PF}$, there are values of the intake rate which lead to values of B_1 below $\overline{B}$, because $\partial B_1 / \partial \rho < 0$. As the reserve's response in period 2 depends on B_1, it is possible to discern threshold values for the intake rate which - under the respective assumption of foresight - indicate whether it is idle, takes in or injects allowances. In fact, there may exist an intake rate for which the relative shift in scarcity leads to a ceasing of banking, i.e. $B_1 = 0$. We call this value $\bar{\rho}_{PF}$. It is calculated by assuming $\underline{B} > B_1 > 0$, i.e. the system is in banking mode and the reserve injects allowances in period 2, and then assessing the critical value of the intake rate at which firms would be indifferent between banking and not banking.

$$\bar{\rho}_{PF} = \frac{(1+r)B_0 + a - r(U-S)}{(2+r)B_0}$$

The reserve will have an effect on market outcomes iff $\rho \geq \bar{\rho}_{PF}$. For smaller values of ρ, intertemporal arbitrage outbalances reserve interactions resulting in a smaller aggregate bank between periods when compared to the reference scenario. As soon as the intake of allowances leads to a breakdown of intertemporal arbitrage, prices go up in period 1, down in period 2 and TACs are higher with the reserve in place (see also Perino & Willner (2016)). We use the subscript "R" to indicate values with a reserve mechanism.

$$(\mathrm{TAC}_{\mathrm{PF,R}}|\rho \geq \bar{\rho}_{PF}) - (\mathrm{TAC}_{\mathrm{PF,R}}|\rho < \bar{\rho}_{PF})$$
$$= \frac{2c}{3(1+r)(2+r)}(a + B_0(1 + r - (2 + r)\rho) + r(S - U))^2 > 0$$

Figure 3 shows B_1 with and without a reserve policy under perfect foresight and figure 4 shows TACs respectively. Of course it is possible that $\bar{\rho}_{PF} \geq 1$. In this case the reserve mechanism is fully redundant.

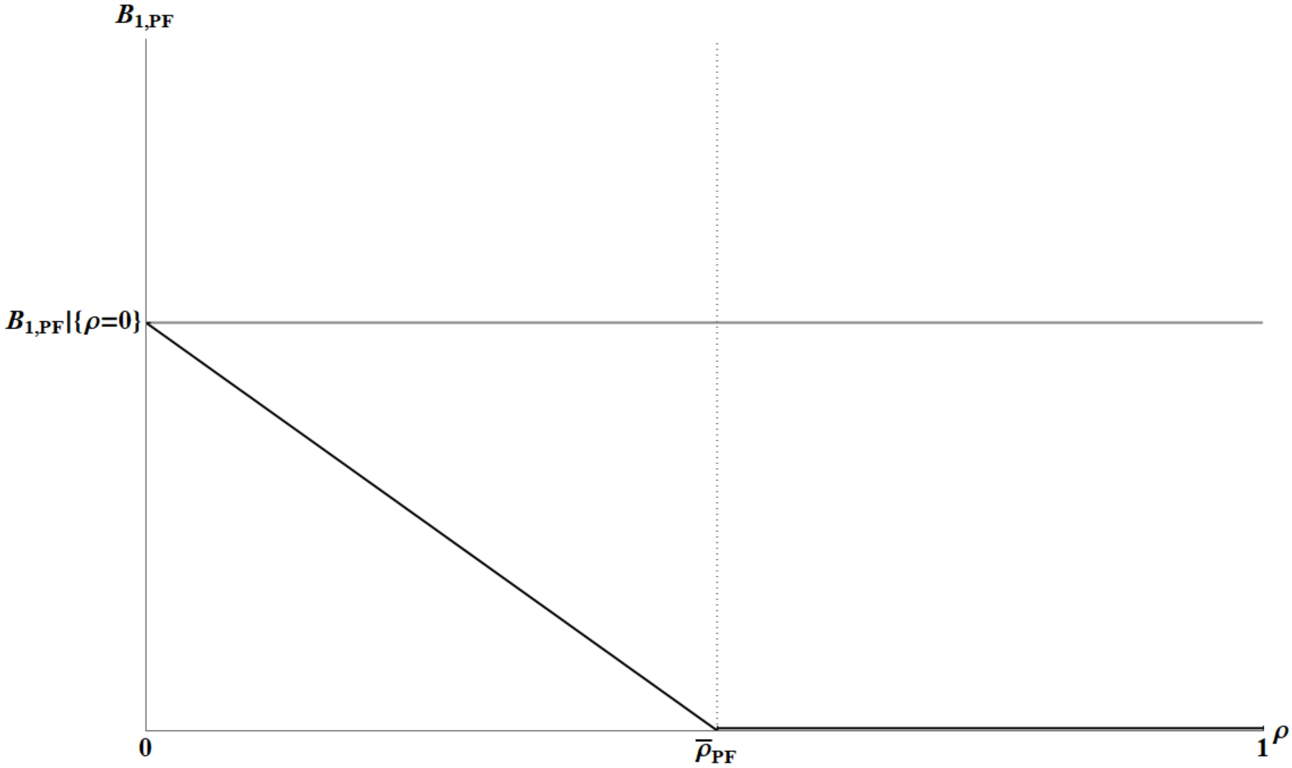

Figure 3: The grey horizontal line represents $B_{1,PF}$ under given parameters without the reserve mechanism in place. The black line shows $B_{1,PF,R}$ as a function of ρ as it decreases due to intertemporal arbitrage and eventually reaches zero at $\bar{\rho}_{PF}$.

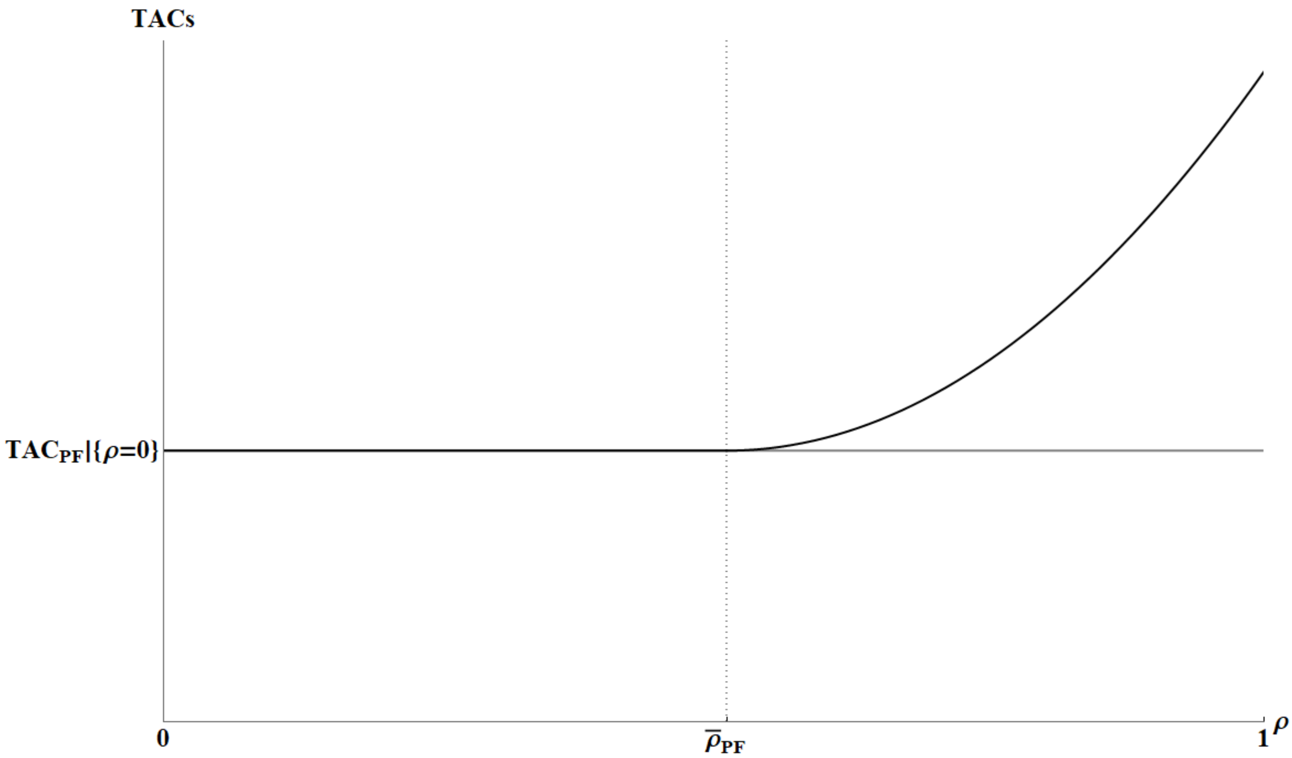

Figure 4: TACs under perfect foresight without the reserve are depicted in grey while black otherwise. As soon as intertemporal arbitrage breaks down, the reserve creates a difference in market outcomes.

3.3 Limited foresight

As we have seen above, limited foresight leads to higher TACs relative to perfect foresight due to non-anticipation of future scarcity and in turn a cessation of banking. This is likewise true for a system with reserve mechanism as only its impact on the allocation for period 1 is taken into account by market participants. Thus, the additional scarcity due to the intake of allowances leads to higher prices in period 1 and consequently lower prices in period 2. By postponing the issue date of allowances, their availability in period 2 rises by ρB_0, cushioning the effect discussed in subsection 2.3. In other words, the reserve functions like a surrogate aggregate private bank, counteracting the difference in market outcome relative to perfect foresight.

In fact, if the amount postponed by the reserve equals the size of the aggregate private bank at $t = 1$, i.e. $\rho B_0 = B^*_{1,PF,R}$, the reserve policy leads to the perfect foresight market outcome of the reference scenario. Then, the available quantities of allowances in both periods would induce exactly the same prices as under perfect foresight.[18] Figure 5 shows TACs depending on ρ. Under the assumptions made, the reserve policy reduces compliance costs by correcting at least partially for limited foresight and the corresponding price effect.

[18] Given the other parameters, we can solve for the intake rate which would guarantee this outcome. This is the case for $\rho = \frac{1}{(2+r)B_0}[(1 + r)B_0 - r(U - S) + a]$. And this is equal to $\bar{\rho}_{PF}$.

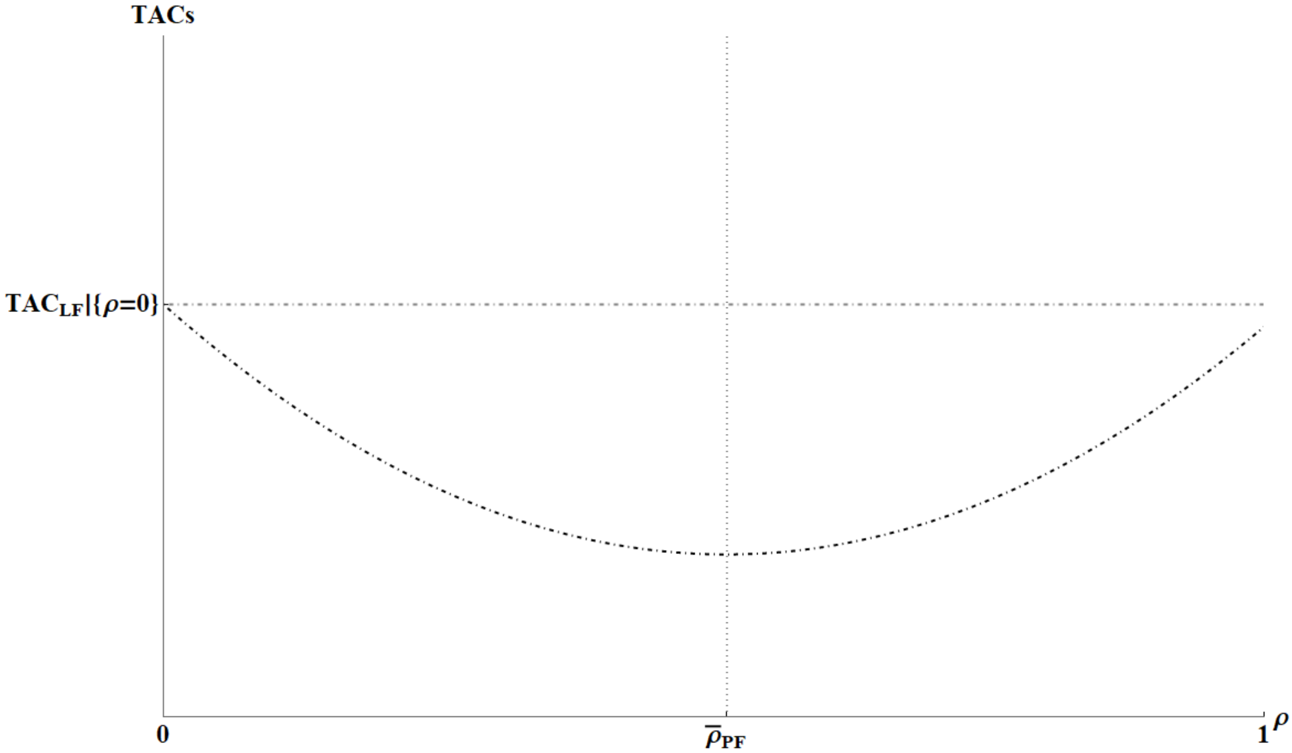

Figure 5: The grey, dash-dotted line shows TACs under limited foresight without a reserve. It has the same origin as with a reserve mechanism which is shown by the black, dash-dotted line. Under limited foresight, TACs are always lower with the reserve mechanism in place. The vertical dotted line marks where the reserve pushes TACs down to the optimal level under perfect foresight without the policy in place.

3.4 Imperfect foresight

The extrapolation of current conditions into the future leads firms' to expect greater scarcity induced by the reserve in period 2 as well. Witnessing the intake of ρB_0 allowances in period 1, they expect a reduction over both periods of $2\rho B_0$. Because of this, firms bank less in aggregate relative to the imperfect-foresight no-policy scenario as $B_{1,IF} > B_{1,IF,R}$ and $\partial B_{1,IF,R}/\partial\rho < 0$ (see Annex **??**). In consequence, prices will be higher in period 1 and lower in period 2 when the reserve releases allowances. This change in prices has varying impacts on TACs. It is possible that the reserve corrects for the underestimation of future scarcity, but no necessarily so. It could also overcompensate for it. We can investigate this by looking at the difference of TACs between the imperfect foresight scenario with and without the reserve:

$$\text{TAC}_{\text{IF}} - \text{TAC}_{\text{IF,R}} = \frac{8cB_0\rho(a - \rho B_0)}{3(1+r)(2+r)}$$

Unsurprisingly, TACs are identical for $\rho = 0$. Moreover, they are identical for $\rho = a/B_0$. For values of the intake rate between these points, TACs with the reserve are lower than without it with a minimum at ρ^*_{IF}:

$$\frac{\partial(\text{TAC}_{\text{IF}} - \text{TAC}_{\text{IF,R}})}{\partial \rho} = \frac{8cB_0(a - 2\rho B_0)}{3(1+r)(2+r)} = 0 \implies \rho^*_{IF} = \frac{a}{2B_0}$$

$$\frac{\partial^2(\text{TAC}_{\text{IF}} - \text{TAC}_{\text{IF,R}})}{\partial \rho^2} = \frac{-16cB_0^2}{3(1+r)(2+r)} < 0$$

This minimum has another interesting feature because it also marks the intake rate at which the reserve corrects for imperfect foresight when compared to the perfect foresight no-policy scenario, i.e. $\text{TAC}_{\text{IF,R}}|\{\rho = \rho^*_{IF}\} = \text{TAC}_{\text{PF}}$. As future scarcity by exogenous cap reductions is not taken into account initially, the reserve serves as a proxy to correct this error of extrapolation to a certain degree. As it stands in for the otherwise lacking scarcity signal it counteracts the otherwise dynamically inconsistent behaviour of firms. To sum up, TACs with the reserve are lower than without it for all $\rho \in (0, min[\frac{a}{B_0}; 1])$. When this is no longer the case and $\rho > min[\frac{a}{B_0}; 1]$, TACs increase due to erroneously perceived future scarcity induced by the reserve. Graph 6 shows TACs and the region of ρ under given parameters where the implementation of the reserve policy reduces abatement costs.

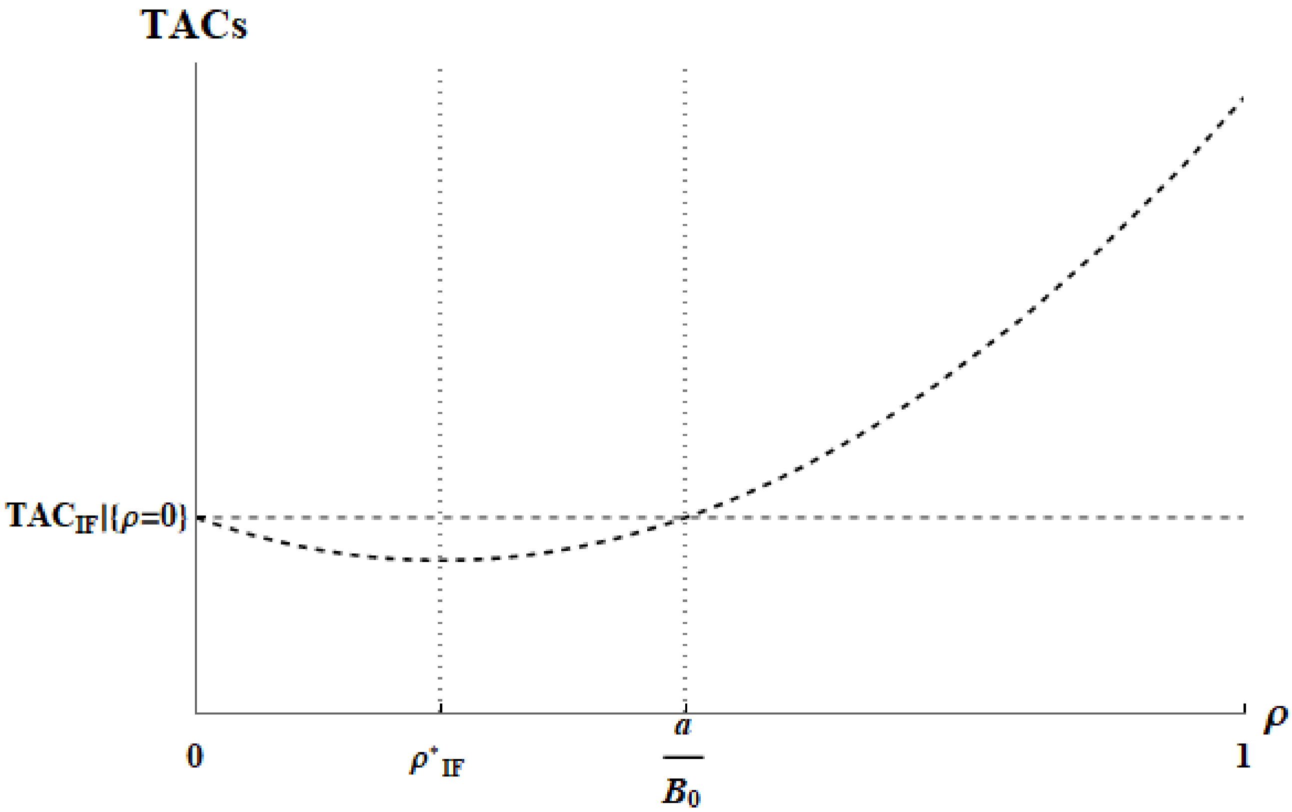

Figure 6: TACs under imperfect foresight are depicted by the grey, dashed line in case of no reserve and by the black, dashed line in case with a reserve in place. For values of the intake rate below $\frac{a}{B_0}$, the reserve reduces costs. For this graph, we use $a = 7$ for a better representation of the region between 0 and $\frac{a}{B_0}$.

3.5 Prices and costs compared

The intertemporal reallocation undertaken by the reserve has ambiguous effects on TACs depending on the foresight scenario applied to the model. Under perfect foresight, gross societal costs with the reserve are at least as high as without it, increasing the burden as soon as it leads to a break-down of intertemporal arbitrage. However, under imperfect and especially under limited foresight, correcting for under-estimated future scarcity may lead to overall less costly market outcomes while still assuring cap-induced emission reductions. Figure 7 compares TACs for the different foresight scenarios relative to the baseline scenario under perfect foresight and no reserve.

Looking at price levels adds another dimension to why implementing a reserve mechanism might be deemed worth the undertaking even though TACs increase. As argued by Edenhofer et al. (2017) and Fuss et al. (2018), current low prices for emissions caused by constrained foresight could be a reason for less than optimal investment into low-carbon technologies as firms would need a stronger monetary incentive sooner than later. As discussed separately above, the reserve mechanism might remedy this as it increases short-term prices while reducing long-term prices except under perfect foresight for all $\rho < \bar{\rho}_{PF}$. Especially under limited and imperfect foresight the reserve mechanism has the potential to steer the market outcome towards TACs under perfect foresight and increase period 1 prices at the same time. Certainly, this presumes the perfect foresight no-policy scenario outcome to be the adequate response to the climate externality. Figure 8 shows the policy-induced difference of current value prices for period 1 for the different scenarios respectively.

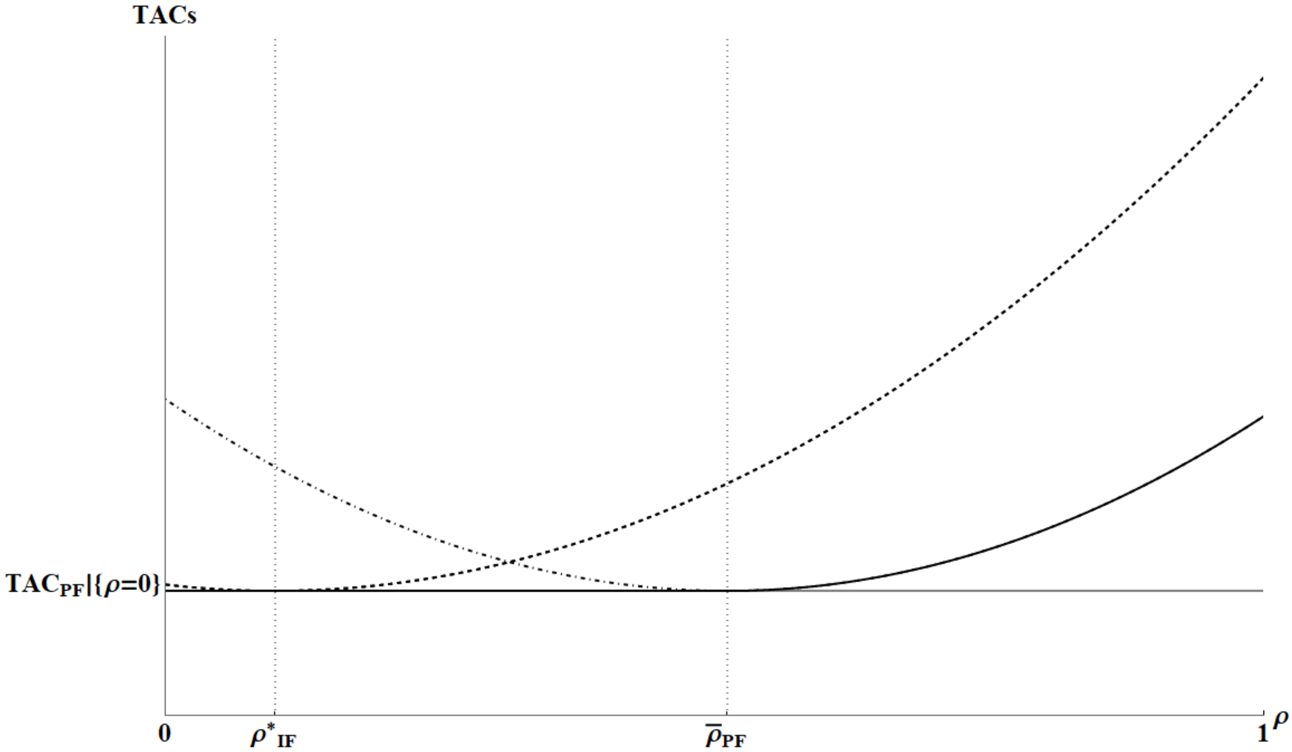

Figure 7: TACs with a reserve in place are shown for perfect foresight (solid black), limited foresight (dot-dashed black) and imperfect foresight (dashed black) as well as for the reference scenario without a reserve under perfect foresight (solid grey).

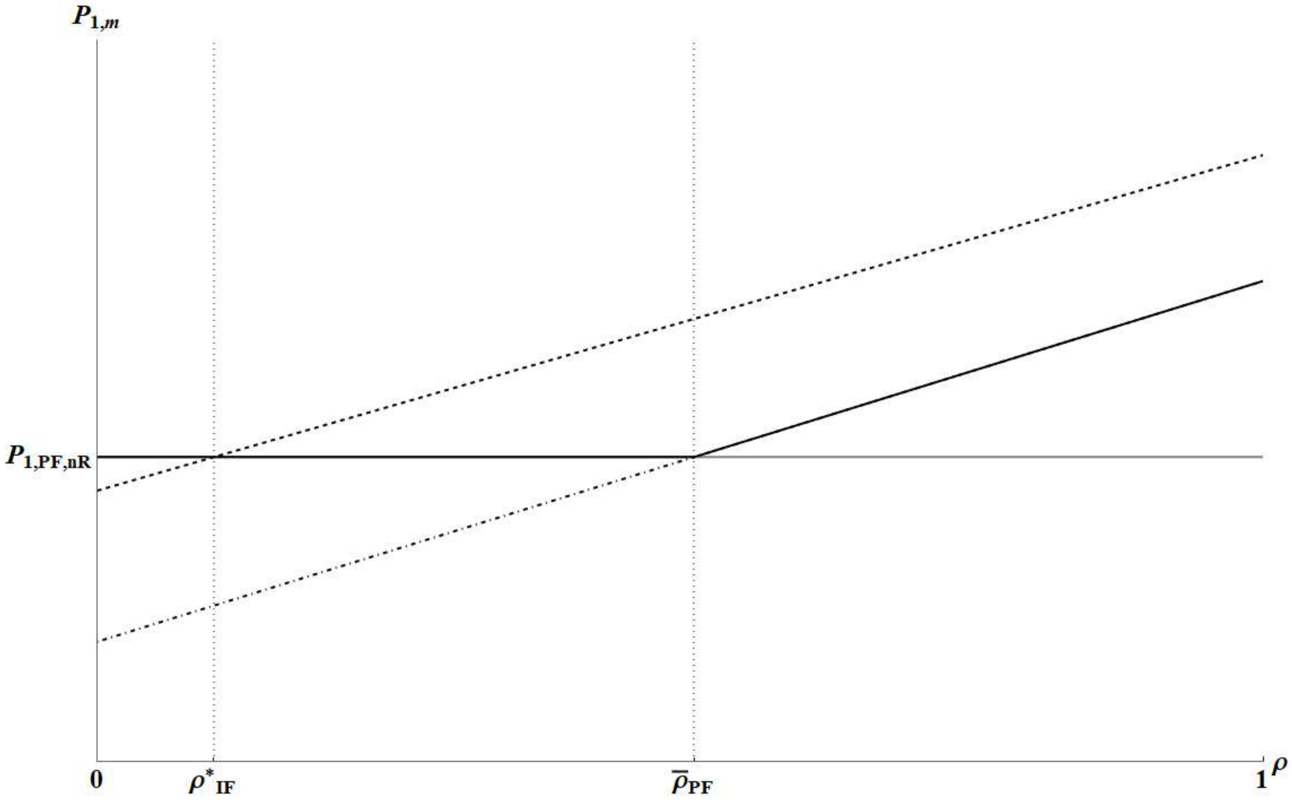

Figure 8: Prices in period 1 as a function of ρ are presented for perfect foresight (solid black), limited foresight (dot-dashed black) and imperfect foresight (dashed black). The grey horizontal line marks $P_{1,PF}$ in abscense of a reserve. Except for the intersections of price functions at ρ^*_{IF} and $\bar{\rho}_{PF}$, the reserve policy generates prices divergent from the optimal level achieved under perfect foresight. As long as there is intertemporal arbitrage under perfect foresight, the reserve is redundant and the price level identical to the no-policy scenario.

4 Cancellations

The 2018 reform of the EU ETS (European Parliament and Council, 2015, 2018) introduces a reserve which features an endogenous cancellation mechanism. Starting in 2023, the number of allowances stored in the MSR may not exceed the amount of auctioned allowances of the previous calendar year. Any surpassing amount will be cancelled from the reserve. Hence it will depend on the banking behavior of market participants how many allowances are priorly taken in and thus how large the reserve it will be by the end of 2022 (see Perino (2018) for more details and implications). To model a cancellation of allowances, only a share of $(1 - \phi)$ allowances in the reserve will return to the market in period 2 with $\phi \in [0; 1]$. If $\phi = 0$, the reserve acts according to the MSR proposed by the EC in 2015 i.e. it does not cancel allowances, while a share of $\phi > 0$ indicates an endogenously determined net reduction of overall supply.

Table 2 shows canceled quantities (c.q.) given values for B_1. As stated in subsection 3.1, due to the structure of the model limiting the scheme to two periods, the flow-back from the reserve in period 2 without cancellations is always an injection of ρB_0, i.e. of the amount previously taken in. With $\phi > 0$ this is no longer the case, as the reserve's period 2 interaction is subtracted from the reserve and subject to cancellations.

Table 2: S_2 depending on B_1 with cancelled quantities (bold).

B_1	$> \overline{B}$	$\leq \overline{B} \wedge \geq \underline{B}$	$< \underline{B} \wedge \geq 0$
S_2	$S - a - \rho B_1 + (1-\phi)(\rho B_0 + \rho B_1)$	$S - a + \phi(\rho B_0)$	$S - a + I + (1-\phi)(\rho B_0 - I)$
c.q.	$\boldsymbol{\phi(\rho B_0 + \rho B_1)}$	$\boldsymbol{\phi \rho B_0}$	$\boldsymbol{\phi(\rho B_0 - I)}$

In comparison to the mechanics of the EU ETS, this model does not allow for the possibility that nothing is cancelled.[19] However, using a cancellation share and not an invariable lump-sum reduction allows for a general investigation of endogenous reductions of the cap. In the following, we compare the scheme with a reserve mechanism with and without cancellations to work out differences to what we discussed in section 3.

4.1 Perfect Foresight

When perfectly foreseen, cancellations in period 2 are correctly taken into consideration for the price expectation of market participants. The larger ϕ, the scarcer allowances will be overall, which in turn leads to elevated prices in both periods as long as there is intertemporal arbitrage, i.e. $B_1 > 0$. Otherwise, cancellations will only increase prices in period 2. In consequence, keeping the system in sufficient supply to induce banking strengthens the price signal already in period 1 and makes cancellations a tool to deliver immediate incentives for increased abatement efforts. Another aspect of endogenous cancellations is their influence on the reserve's interaction. Increased overall scarcity translates into lower values for the relevant ρ at which firms's optimization would lead to e.g. the reserve to remain idle in period 2 ($\overline{B} \geq B_1 \geq \underline{B_1}$). Due to the discrete nature of the reserve's impact on the allocation schedule ($-\rho B_1$ to 0 and 0 to $+I$), there are regions of ρ where multiple equilibria are possible: For a given intake rate, firms' optimization can lead to different levels of B_1 – in turn resulting in a different reserve reaction in period 2. We choose to follow the optimal path along firms' minimal aggregate compliance costs (FCCs) which take into account TACs as well as the financial resources spent on net acquisition of allowances per period, i.e. $P_1 S_1$ and $(P_2 S_2)/(1+r)$. Figure 9 shows FCCs under perfect foresight with 40% cancellations, i.e. $\phi = 0.4$. We opt to use the lower FCC-values in the overlapping regions as they are Pareto optimal from the regulated sector's perspective. For demonstrational reasons, we use parameters that allow for optima in all interaction modes of the reserve, i.e. we assure that $\overline{B} - \underline{B} > \frac{1-\phi}{2+r} I$. Otherwise, regardless of the value of ρ, the reserve would never be idle in equilibrium. A derivation of threshold values for the intake rate and intuition for our choice can be found in Annex **??**.

[19] In the EU ETS, no cancellations would occur when the amount of allowances in the reserve doesn't exceed the amount of auctioned allowances in the previous year.

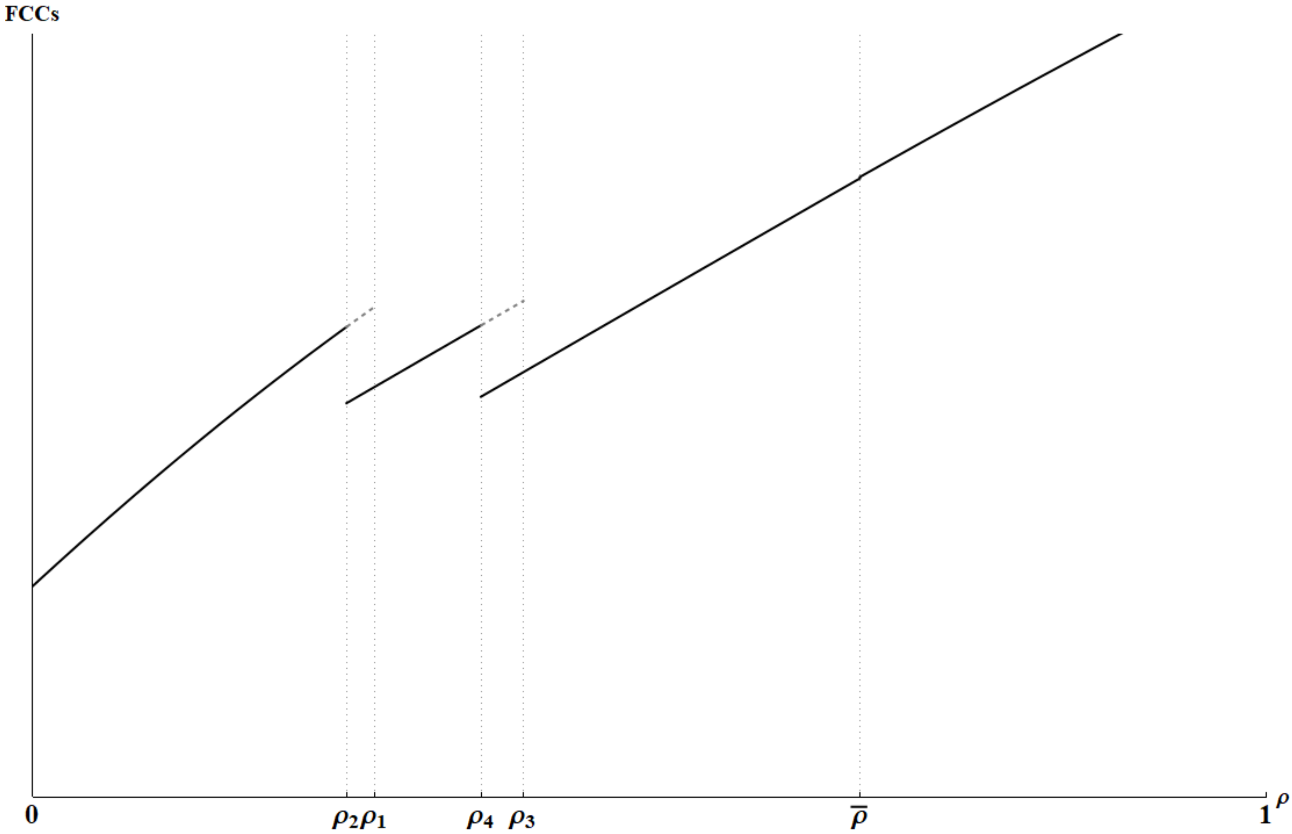

Figure 9: FCCs for different values of ρ, supressing the subscript "PF,c". Depending on the mode of the reserve interaction, the corresponding threshold values of B_1 will be reached at different values of ρ, e.g. at $\rho = \rho_1$, we have $B_1 = \overline{B}$ given the reserve takes in allowances until then. However at $\rho = \rho_2$, we have $B_1 = \overline{B}$ given the reserve is idle (until $\rho = \rho_3$ and $B_1 = \underline{B}$). At $\rho = \rho_4$ we have $B_1 < \underline{B}$ given the reserve injects I. FCCs thus depend on the optimal path of firms' emissions which again depend on the mode of the reserve interaction. We use the path minimizing FCCs depicted in black with mode switches at ρ_2 and ρ_4. We choose $I = 1.5$ and $a = 5$ for better resolution.

To give a better intuition for the impact of endogenous cancellations, we opt for a representation of TACs a a function of both ρ and ϕ. With this, we move away from cost-effectiveness analysis, as the total amount of allowances is now endogenous, too, i.e. the cap is does no longer decline at a constant rate. For our purpose at hand, benefits from the more stringent cap are not taken into account. Figure 10 shows the difference of these costs between the system with reserve and cancellations (c) and the system with reserve and no cancellations, i.e. $\Delta TAC_{PF,R} = TAC_{PF,R,c} - TAC_{PF,R}$.
It shows the amplification of jumps at the mode-switches of the reserve's interactions with allowances supply as greater cancellations increase inter-period scarcity. Moreover, the junctions do not run straight horizontally to the ϕ-axis because of the impact of cancellations on threshold values, i.e. $\partial\rho_{k,PF,c}(\phi)/\partial\phi > 0$, $k \in \{0, ..., 4\}$. Endogenous cancellations increase the incentive to bank, resulting in larger $B_{1,R,c}$. As threshold intake rates differ from before, there exists a set of values of the intake rate and cancellation rate where the reserve would still be idle without cancellations while it would already inject allowances with cancellations. This is the reason for the subpartition of the plane between $\rho_{4,PF,c}(\phi)$ and $\bar{\rho}_{PF,c}(\phi)$.

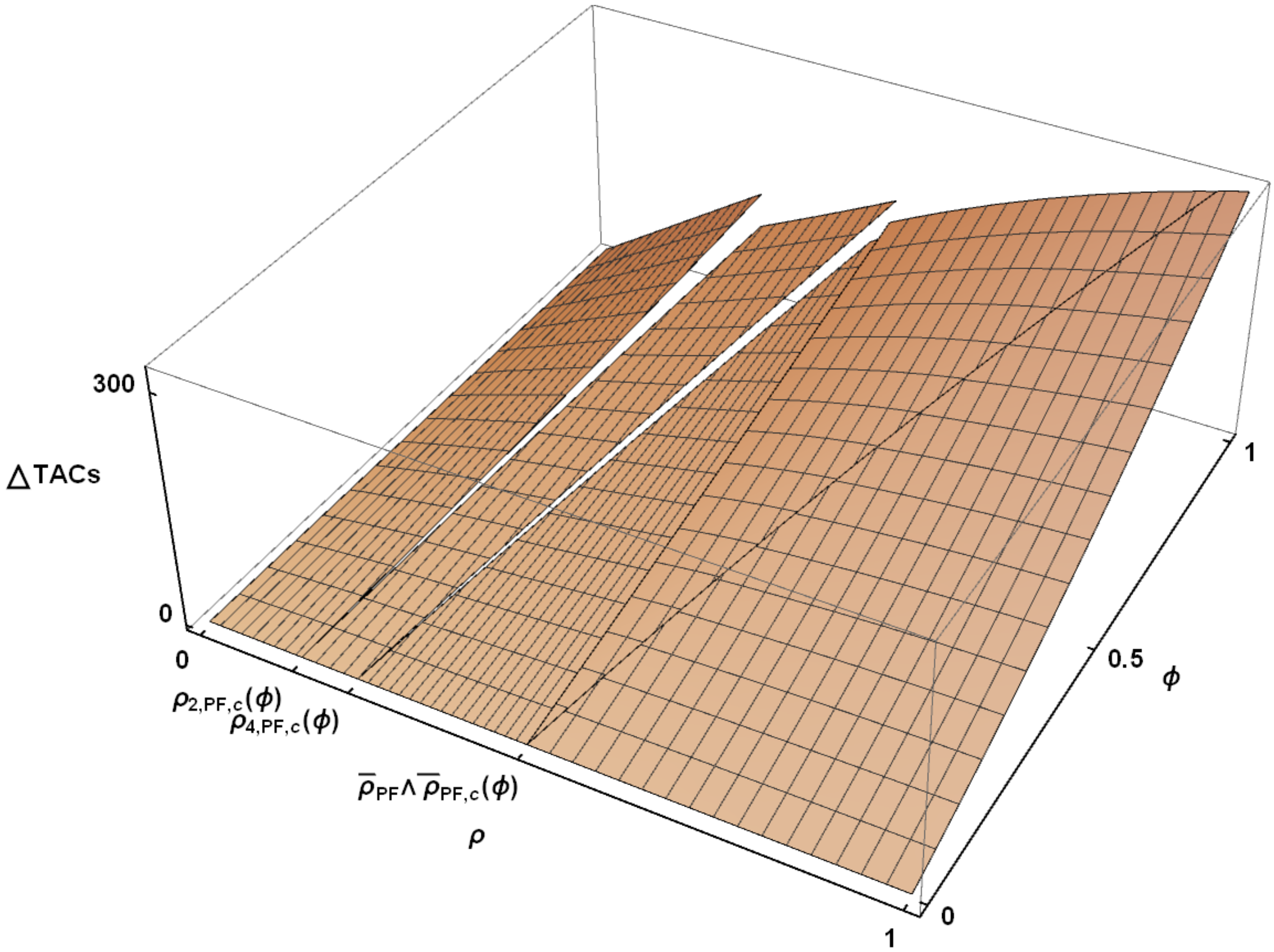

Figure 10: Endogenous cancellations inrease TACs both in the intake rate as well as the cancellation rate. As cancellations in period 2 become larger, relative scarcity between periods increases as well as the incentive to bank *ceterus paribus*. Hence threshold intake rates increase as well.

4.2 Limited Foresight

With limited foresight, cancellations have no impact on short-term scarcity and hence on prices in period 1. Instead, they only affect allocation quantities in period 2 and raise prices there, just like under perfect foresight with no banking. Because of this, the reduction of price appreciation due to the dynamic backloading aspect of the reserve is dampened by the cancellation aspect, i.e. the surrogate private bank effect of the reserve (see subsection 3.3) is counteracted and reduced. The consequence are overall higher TACs without further adding to investment incentives. Nevertheless, relaxing the notion that the perfect foresight reference case is the desired outcome, cancellations reduce the risk of slumbing prices in period 2 due to reserve-induced higher abatement acitivities in period 1. In view of the goal of price stability enshrined in the formulations of the latest EU reform Directive 2018/410, supporting long-term prices might help sustaining investment when the reserve feeds back allowances. This is an interesting route for further research. Figure 11 shows the joint effect of the intake rate and the share of cancelled allowances.

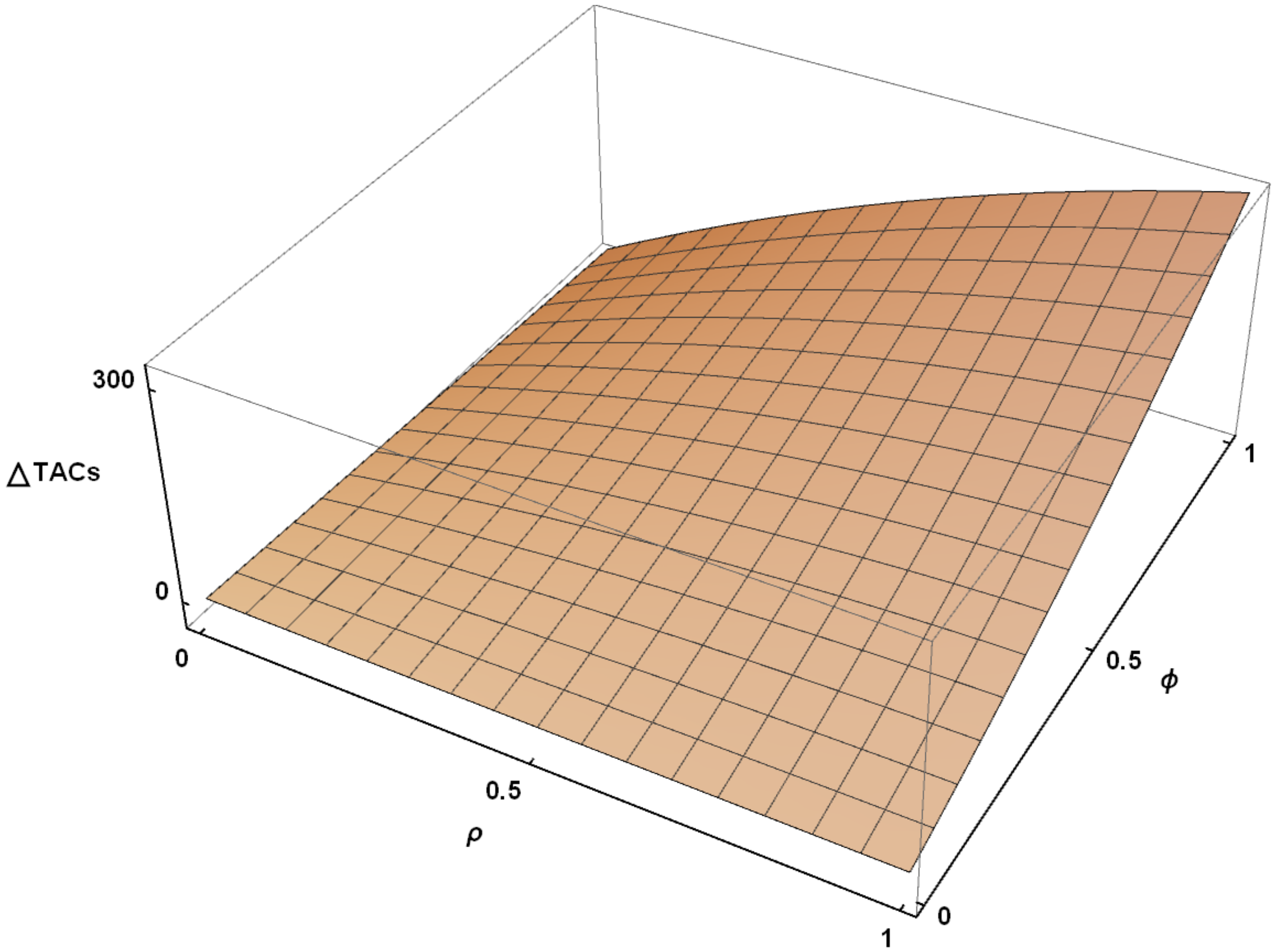

Figure 11: As both periods are distinctly separated, including cancellations into the system leads to increased TACs and and higher prices in period 2.

4.3 Imperfect Foresight

Under imperfect foresight, cancellations are not foreseen and do not have an impact on prices in period 1 in result of the firms' first stage optimization just like under limited foresight. However, this affects threshold junctions, too. In contrast to perfect foresight, they are not curved, because $\rho_{k,IF}$ are derived from period 1 expectations and hence do not depend on the cancellation share. Furthermore, higher expected scarcity under imperfect foresight leads to a stronger incentive to bank than under perfect foresight and thus keeps firms' optimization behavior more resistive to undercutting $\overline{B}$. This can lead to an exclusion of intervention modes of the reserve when some $\rho_{k,IF,c} \geq 1$. The system under imperfect foresight is hence less likely to reach a reserve-induced breakdown of intertemporal arbitrage compared to perfect foresight given the same intake rate and cancellation share. Cancellations increase TACs in all cases by reducing overall allocation by at least $\phi\rho B_0$. Other than that, the effects of cancellations in counteracting dynamic backloading are comparable to the limited foresight scenario.

Figure 12 shows TACs with respect to both the intake rate and the cancellation share.

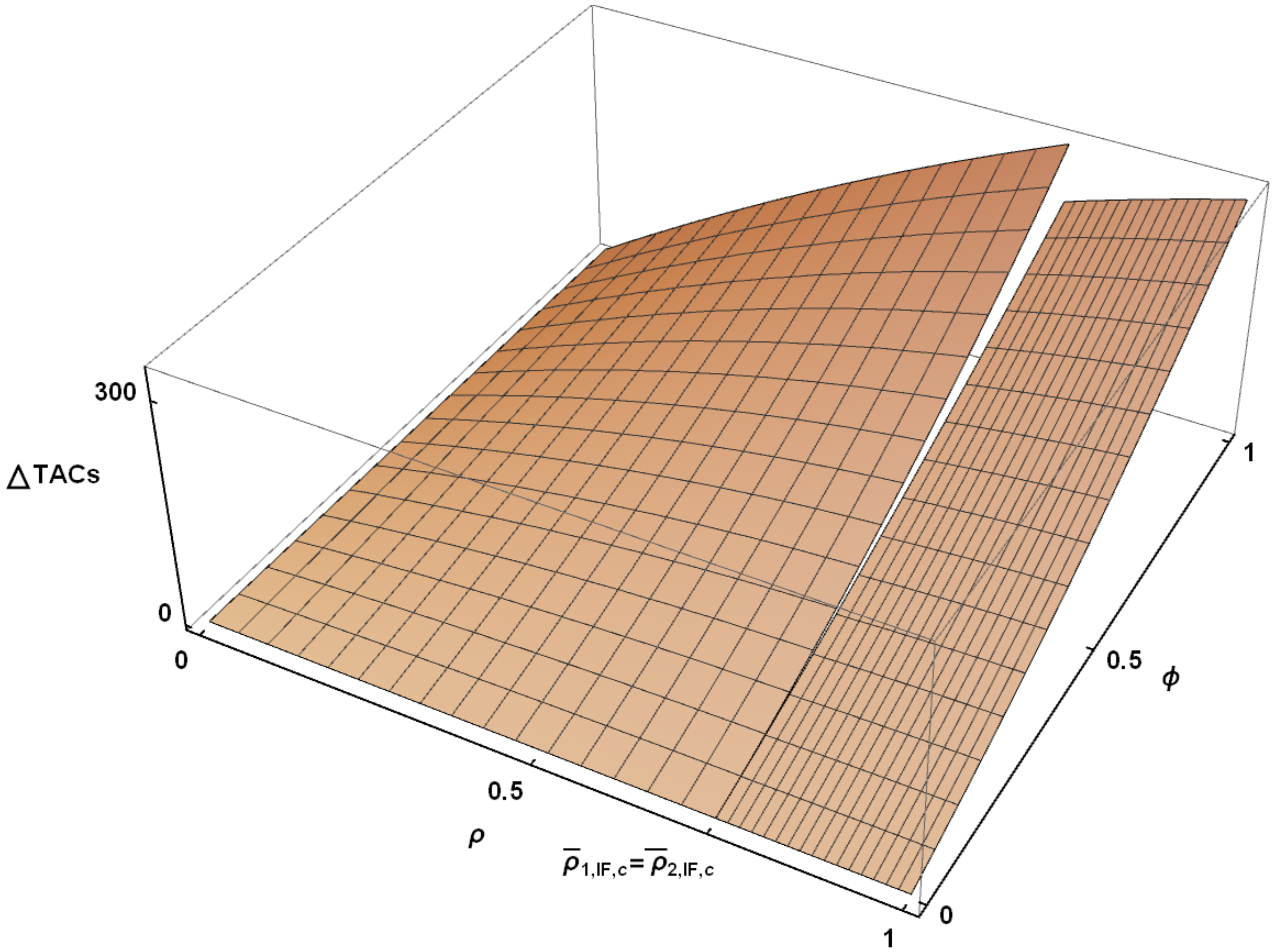

Figure 12: The difference in TACs caused by endogenous cancellations is only shown for when the reserve takes in allowances in period 2 and when it is idle. The relevant threshold values for ρ to induce injections or to break down intertemporal arbitrage lie outside the parameter range, i.e. $1 > \rho_{k,IF,c} \backslash \{k = 1\}$

.

5 Conclusion

Following a long period of carbon prices far below the expectations of policy makers and estimates of the social cost of carbon, the EU passed a reform of the EU ETS to take effect in 2019. With the Market Stability Reserve and other measures, the reform shall make the system more resilient to supply and demand imbalances, produce a stable price signal and incentivize market participants to invest more timely and strongly in low-carbon technologies. Implicitly, the latter objective calls for an increase of short-term prices for allowances, which is the dominant issue in current policy debates concerning the future of the EU ETS.

The MSR is a reserve mechanism which firstly postpones the issue dates of allowances (dynamic backloading) and secondly reduces the overall cap by endogenous cancellations. Its impact depends on how market participants react to the change in the supply schedule and the added complexity of the system. In this paper, we studied the implications of a MSR-like reserve mechanism in different scenarios of firms' foresight and investigated total abatement costs and

prices in a perfectly competitive market for emission allowances. In our two-period partial equilibrium model, we distinguished between perfect, limited and imperfect foresight. Both deviations from perfect foresight constitute market failures which lead to an underestimation of long-term scarcity. This brings about a smaller aggregate bank, lower short-term prices (period 1), higher long-term prices (period 2) and therefore overall higher total abatement costs.
If one assumes total supply to be adequately calibrated to the climate externality, prices and total abatement costs under perfect foresight constitute a benchmark for the success of the reserve in steering market outcomes away from their limited or imperfect foresight equilibria.
We find that the dynamic backloading aspect of the reserve increases short-term prices and reduces long-term prices in both deviating scenarios. Shifting allowance supply to the future can correct for the market failure by functioning as a surrogate aggregate bank. In both scenarios the reserve can however also lead to short-term (long-term) prices higher (lower) than under perfect foresight, leading again to higher total abatement costs. From a cost-effectiveness point of view, the reserve might be an improvement given the regulator chooses the reserve's intake rate accurately. Under imperfect foresight, the accurate intake rate is lower than under limited foresight, hence clarity about market participant's foresight is a prerequisite for sound reform the regulator needs to be aware of.
However, the 2019 reform of the EU ETS also entails endogenous cancellations starting in 2023. Such cancellations always increase total abatement costs in every scenario of foresight by reducing the overall supply. They will only affect short-term prices under perfect foresight as long as firms bank allowances. Otherwise, they lead to an increase of long-term prices only. In other words, cancellations only achieve a strengthening of the short-term price signal under perfect foresight while dynamic backloading has no effect due to intertemporal arbitrage. Furthermore, the cancellation mechanism moves market outcomes under limited and imperfect foresight away from the perfect foresight reference equilibrium, counteracting the correcting effects of dynamic backloading. Since we did not investigate additional benefits from cap reductions as the result of cancellations, it remains to future research to delve into the relative cost-effectiveness of endogenous cancellations in comparison to other possibilites to curb supply. Considering the diverse effects discussed above, this puzzle only makes sense if a second market failure next to impaired foresight is present, too. Maladjusted supply would result in a market equilibrium under perfect foresight with carbon prices below the social cost of carbon. Then, dynamic backloading and cancellations combined could deliver wanted outcomes in terms of higher short-term prices as well as less overall supply in one swoop. This being said, it is fathomable that the driving reason behind the choice of a rather complex reserve-and-cancel-mechanism is the failure of the regulator to curb supply *and* her perception that firms do not experience perfect foresight. Otherwise, either endogenous cancellations (limited and imperfect foresight) or dynamic backloading (perfect foresight with banking) were unsuitable for delivering stronger investment incentives in the short run.
Learning more about firms' actual behavior in the EU ETS and the procedures of manegerial decision making in carbon markets will certainly add to the improvement of reform. The current

design for 2019 onwards is suited to deliver empirical data which will hopefully help devising less complex yet more targeted carbon pricing policies.

References

Barberis, N., Greenwood, R., Jin, L., & Shleifer, A. (2015). X-CAPM: An extrapolative capital asset pricing model. *Journal of Financial Economics*, 115(1), 1–24.

BMU (2018). *Klimaschutzbericht 2017 - Zum Aktionsprogramm Klimaschutz 2020 der Bundesregierung*. Technical report, Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, Berlin.

Böhringer, C., Löschel, A., Moslener, U., & Rutherford, T. E. (2009). EU climate policy up to 2020: An economic impact assessment. *Energy Economics*, 31, 295–305.

Borenstein, S., Bushnell, J., Wolak, F. A., & Zaragoza-Watkins, M. (2015). *Expecting the unexpected: Emissions uncertainty and environmental market design*. Technical report, National Bureau of Economic Research.

Bray, M. (1987). *The New Palgrave: A Dictionary of Economics*, chapter Perfect Foresight, (pp. 833–834). Macmillan.

Chen, Y. & Tanaka, M. (2018). Permit banking in emission trading: Competition, arbitrage and linkage. *Energy Economics*, 71, 70–82.

Convery, F. J. (2009). Origins and development of the EU ETS. *Environmental and Resource Economics*, 43(3), 391–412.

Cramton, P. & Kerr, S. (2002). Tradeable carbon permit auctions: How and why to auction not grandfather. *Energy policy*, 30(4), 333–345.

Cronshaw, M. B. & Kruse, J. B. (1996). Regulated firms in pollution permit markets with banking. *Journal of Regulatory Economics*, 9(2), 179–189.

De Perthuis, C. et al. (2011). Carbon markets regulation: The case for a CO2 central bank. *Climate economics chair information and debates series*.

DG Climate Action (2015). EU ETS Handbook. European Commission.

Edenhofer, O., Flachsland, C., Wolff, C., Schmid, L., Leipprand, A., Koch, N., Kornek, U., & Pahle, M. (2017). Decarbonization and EU ETS Reform: Introducing a price floor to drive low-carbon investments. *Mercator Research Institute on Global Commons and Climate Change (MCC) Policy Paper*.

Erickson, P., Kartha, S., Lazarus, M., & Tempest, K. (2015). Assessing carbon lock-in. *Environmental Research Letters*, 10(8), 084023.

European Commission (2014). *Q&A on ETS market stability reserve.* Technical Report MEMO/14/39, European Commission.

European Commission (2018). *Public of the total number of allowances in circulation for the purposes of the Market Stability Reserve under the EU Emissions Trading System established by Directive 2003/87/EC - C2018 2801 final.* Technical Report C(2017) 3228 final, European Commission.

European Parliament and Council (2015). Decision (eu) 2015/1814 of the european parliament and of the council of 6 october 2015 concerning the establishment and operation of a market stability reserve for the union greenhouse gas emission trading scheme and amending directive 2003/87/ec. *Official Journal of the European Union*, 58, L264/1–L264/5.

European Parliament and Council (2018). DIRECTIVE (EU) 2018/410 to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814. *Official Journal of the European Union*, L 76/3.

Fuss, S., Flachsland, C., Koch, N., Kornek, U., Knopf, B., & Edenhofer, O. (2018). A Framework for Assessing the Performance of Cap-and-Trade Systems: Insights from the European Union Emissions Trading System. *Review of Environmental Economics and Policy.*

Gerlagh, R. & Heijmans, R. J. (2018). Regulating Stock Pollutants. *Working Paper.*

Gerlagh, R. & Liski, M. (2018). Carbon prices for the next hundred years. *The Economic Journal*, 128(609), 728–757.

Grosjean, G., Acworth, W., Flachsland, C., & Marschinski, R. (2016). After monetary policy, climate policy: is delegation the key to EU ETS reform? *Climate Policy*, 16(1), 1–25.

Hahn, R. W. & Stavins, R. N. (2011). The effect of allowance allocations on cap-and-trade system performance. *The Journal of Law and Economics*, 54(S4), S267–S294.

Heemeijer, P., Hommes, C., Sonnemans, J., & Tuinstra, J. (2009). Price stability and volatility in markets with positive and negative expectations feedback: An experimental investigation. *Journal of Economic dynamics and control*, 33(5), 1052–1072.

High-Level Commission on Carbon Prices (2017). *Report of the High-Level Commission on Carbon Prices.* Technical report, World Bank, Washington, D.C.

Hintermann, B., Peterson, S., & Rickels, W. (2015). Price and Market Behavior in Phase II of the EU ETS: A Review of the Literature. *Review of Environmental Economics and Policy*, 10(1), 108–128.

Holt, C. A. & Shobe, W. M. (2016). Price and quantity collars for stabilizing emission allowance prices: Laboratory experiments on the EU ETS market stability reserve. *Journal of Environmental Economics and Management*, 76, 32–50.

Hommes, C., Sonnemans, J., Tuinstra, J., & Van de Velden, H. (2004). Coordination of expectations in asset pricing experiments. *The Review of Financial Studies*, 18(3), 955–980.

Jarke, J. & Perino, G. (2017). Do renewable energy policies reduce carbon emissions? On caps and inter-industry leakage. *Journal of Environmental Economics and Management*, 84, 102–124.

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics*, 34(1), 1–23.

Knopf, B., Koch, N., Grosjean, G., Fuss, S., Flachsland, C., Pahle, M., Jakob, M., & Edenhofer, O. (2014). *The European Emissions Trading System (EU ETS): Ex-Post Analysis, the Market Stability Reserve and Options for a Comprehensive Reform.* Note di lavoro 2014.079, FEEM.

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

Koch, N., Grosjean, G., Fuss, S., & Edenhofer, O. (2016). Politics matters: Regulatory events as catalysts for price formation under cap-and-trade. *Journal of Environmental Economics and Management*, 78, 121–139.

Kollenberg, S. & Taschini, L. (2016). Emissions trading systems with cap adjustments. *Journal of Environmental Economics and Management*, DOI: 10.1016/j.jeem.2016.09.003.

Kollenberg, S. & Taschini, L. (2018). Dynamic Supply Adjustment and Banking under Uncertainty: the Market Stability Reserve. *unpublished*.

Muth, J. F. (1961). Rational expectations and the theory of price movements. *Econometrica: Journal of the Econometric Society*, (pp. 315–335).

Neuhoff, K., Martinez, K. K., & Sato, M. (2006). Allocation, incentives and distortions: the impact of eu ets emissions allowance allocations to the electricity sector. *Climate Policy*, 6(1), 73–91.

Newbery, D., Reiner, D., & Ritz, R. (2018). When is a carbon price floor desirable? *Cambridge Working Papers in Economics*, (1833).

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. *Journal of the Association of Environmental and Resource Economists*, 1(1/2), 273–312.

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

Perino, G. & Requate, T. (2012). Does more stringent environmental regulation induce or reduce technology adoption?: When the rate of technology adoption is inverted U-shaped. *Journal of Environmental Economics and Management*, 64(3), 456–467.

Perino, G. & Willner, M. (2016). Procrastinating reform: The impact of the market stability reserve on the EU ETS. *Journal of Environmental Economics and Management*, 80, 37–52.

Perino, G. & Willner, M. (2017a). EU-ETS Phase IV: allowance prices, design choices and the market stability reserve. *Climate Policy*, 17/7, 1–11.

Perino, G. & Willner, M. (2017b). Why the EU Market Stability Reserve deters long-term low-carbon investments. *WiSo-HH Working Paper Series*, (44).

Perman, R., Ma, Y., Common, M., Maddison, D., & McGilvray, J. (2011). *Natural Resource and Environmental Economics*. Pearson United Kingdom, 4th edition.

Rubin, J. D. (1996). A model of intertemporal emission trading, banking, and borrowing. *Journal of Environmental Economics and Management*, 31(3), 269–286.

Salant, S. W. (2016). What ails the European Union's Emissions Trading System? *Journal of Environmental Economics and Management*, 80, 6–19.

Schennach, S. M. (2000). The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments. *Journal of Environmental Economics and Management*, 40(3), 189–210.

Schleich, J., Ehrhart, K.-M., Hoppe, C., & Seifert, S. (2006). Banning banking in EU emissions trading? *Energy Policy*, 34(1), 112–120.

Schopp, A. & Neuhoff, K. (2013). The role of hedging in carbon markets. *DIW Berlin Discussion Paper*, (1271).

Tol, R. S. (2009). The economic effects of climate change. *Journal of Economic Perspectives*, 23(2), 29–51.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy policy*, 28(12), 817–830.

Venmans, F. M. J. (2016). The effect of allocation above emissions and price uncertainty on abatement investments under the EU ETS. *Journal of Cleaner Production*, 126, 595–606.

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

A Derivation of critical market interest rate

Solving firm i's optimization problem, eliciting $e^*_{i,t}$ and finding the market equilibrium we can state from equation 1 that:

$$P_{1,PF} + P_{2,PF} = c(2U - B_0 - 2S + a)$$

We know that in case banking ceases, $B_1 = 0$ and in this scenario all firms are either indifferent to bank or to borrow or at least one firm would like to borrow but cannot fulfill its desire to do so. In the latter case, the non-borrowing constraint enters the firm's optimization problem via the switch of purchases in period 1 to a binding condition ($x_{1,i} = e_{1,i} - b_{0,i}$). The multiplicator here called $\lambda_{PF} \geq 0$ represents the shadow price of one more allowance. In this case, $P_{2,PF} = (1 + r)(P_{1,PF} - \lambda_{PF})$. Also, we know that $B_0 + S - E_{1,nb,PF} = 0$ and thus that $P_{1,nb,PF} = c(U - S - B_0)$. Then we can simply plug in and get:

$$\begin{aligned}
P_{1,nb,PF} + (1 + r)(P_{1,nb,PF} - \lambda_{PF}) &= c(2U - B_0 - 2S + a) \\
&\Leftrightarrow \\
(2 + r)P_{1,nb,PF} - c(2U - B_0 - 2S + a) &= (1 + r)\lambda_{PF} \\
&\Leftrightarrow \\
r(U - S - B_0) - B_0 - a &= \frac{1 + r}{c}\lambda_{PF} \\
&\Leftrightarrow \\
r &> \frac{B_0 + a}{U - S - B_0}
\end{aligned}$$

The critical interest rate $\bar{r}_{PF}$ marks the value of r, where the inequality gives way to an equality where all firms are indifferent between banking and borrowing.

B Critical values of r

Without anticipation of the cap reduction in period 2, firms see less scarcity and expect lower prices under imperfect foresight than under perfect foresight. This means that they have a smaller incentive to bank allowances, which is reflected by a smaller critical market interest rate which would entice them to not bank at all.

$$\begin{aligned}
\bar{r}_{IF} &= \frac{B_0}{U - B_0 - S} \\
\bar{r}_{IF} &< \bar{r}_{PF}
\end{aligned}$$

If we choose $r < \bar{r}_{IF}$, we can be sure that firms will bank as well under perfect foresight.

Moreover, if $r \geq \bar{r}_{PF}$, there would be no banking in either scenario.

C Parameters

r	0.15
U	100
B_0	15
S	75
a	3
c	1
ρ	0.24
$\overline{B}$	5.5
$\underline{B}$	3.75
I	1
ϕ	0.4

D TACs w.r.t. r

First, we derive TACs for all three scenarios. TACs are derived for banking mode (PF & IF):

$$
\begin{aligned}
\text{TAC}_{\text{PF}} &= \frac{c}{(2+r)}\left(2U^2 + 2S^2 + \frac{B_0^2 + a^2}{2} - 4US - 2UB_0 + 2Ua + 2SB_0 - 2Sa - B_0 a\right) \\
\text{TAC}_{\text{IF}} &= \frac{c}{(2+r)^2}\left(2U^2 + 2S^2 + \frac{B_0^2}{2} - 4US - 2UB_0 + 2SB_0\right) \\
&+ \frac{c}{(1+r)}\left(\frac{U^2 + S^2 + a^2}{2} - US + Ua - Sa\right) \\
\text{TAC}_{\text{LF}} &= \frac{c}{2}\left(U^2 + S^2 + B_0^2 - 2US - 2UB_0 + 2SB_0\right) \\
&+ \frac{c}{(1+r)}\left(\frac{U^2 + S^2 + a^2}{2} - US + Ua - Sa\right)
\end{aligned}
$$

Now we can check differences:

$$
\begin{aligned}
\text{TAC}_{\text{LF}} - \text{TAC}_{\text{IF}} = &\frac{c}{(2+r)^2}((2 + \frac{r}{2})(U^2 + S^2) + (1.5 + 2r + \frac{r}{2})B_0^2 \\
&- (4r + r^2)US - (2 + 4r + r^2)B_0(U - S)) > 0
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\text{TAC}_{\text{IF}} - \text{TAC}_{\text{PF}} = &\frac{c}{2(1+r)(2+r)^2}(-B_0^2(1+r)^2 + a^2(2+r) + 4B_0(a - S + U) \\
&+ r(2B_0 a(3+r) + r(-3S^2 + 2Sa - 4SB_0 - 3U^2 - 2Ua + 4UB_0 + 6US) \\
&- 4(S^2 - Sa + 2SB_0 + U^2 + Ua - 2(UB_0 + US)))) > 0
\end{aligned} \tag{4}
$$

The parameter space used in this paper to assure overall scarcity of allowances guarantees these differences to be greater than 0, with positive roots at $\bar{r}_{IF}$ for equation 3 and $\bar{r}_{PF}$ for equation 4.

E Interperiod banking under imperfect foresight

First, we need to take a look at period 1 prices, which will feature in the equation for the aggregate bank.

$$P_{1,IF,R}|\{\rho < \bar{r}_{IF,R}\} = \frac{c}{2+r}(2U - 2S - B_0 + 2\rho B_0)$$

This is the price no matter what the actual size of $B_{1,IF,R}$ and the corresponding reserve interaction, since the latter is not foreseen. For the aggregate bank we then get:

$$B_{1,IF,R} = B_0 + S - \rho B_0 - U + \frac{P_{1,IF,R}|\{\rho < \bar{r}_{IF,R}\}}{c}$$

Taking the derivative with respect to the intake rate yields:

$$\frac{\partial B_{1,IF,R}}{\partial \rho} = -\frac{r}{2+r} B_0 < 0$$

Furthermore, the aggregate bank without the reserve is bigger than with it:

$$B_{1,IF} - B_{1,IF,R} = r\rho B_0 \ > 0$$

F FCCs and threshold values

First of all, it is important to define FCCs:

$$\text{FCCs} = \text{TACs} + P_1 S_1 + \frac{P_2 S_2}{1+r}$$

Next, we use the definition of the inter-period aggregate private bank, i.e. $B_1 = B_0 + S_1 - E_1$ and take into account that E_1 depends on the value of ρ and due to perfect foresight the reserve

interaction in period 2, too. It is now possible to check all necessary thresholds by setting the different definitions of B_1 equal to $\overline{B}$, $\underline{B}$ and 0. An example illustrates this procedure.
The reserve always takes in ρB_0 in period 1 and given $B_1 > \overline{B}$, we know that it will reduce period 2 allocations by ρB_1 and feed back $(1-\phi)(\rho B_0 + \rho B_1)$. Since prices rise at the interest rate, we can form an expression for P_1 and replace E_1 in the expression for B_1. Subscript c stands for values with cancellations.

$$P_{1,PF,c}|\{B_1 > \overline{B}\} = \frac{c}{2+r-\rho(1-\phi)}[2U - 2S - B_0 + a + \rho(1-\phi)(2B_0 + S - \rho B_0 - U)]$$

Following, we can solve for ρ.

$$\begin{aligned} B_1 &> \overline{B} \\ &\Leftrightarrow \\ B_0 + S - U + \frac{P_{1,PF,c}|\{B_1 > \overline{B}\}}{c} &> \overline{B} \\ &\Leftrightarrow \\ \rho &< \frac{(1+r)B_0 - (2+r)\overline{B} + a - r(U-S)}{(1+r+\phi)B_0 - (1-\phi)\overline{B}} = \rho_{1,PF,c} \end{aligned}$$

This is ρ_1 in Figure 9 and for all $\rho \leq \rho_1$, optimal firm behavior minimizes FCCs given $B_1 > \overline{B}$, i.e. the reserve takes in allowances in period 2, too. Now, we can check for the implications when the reserve remains idle, i.e. $\overline{B} \geq B_1 \geq \underline{B}$.

$$P_{1,PF,c}|\{B_1 = \overline{B}\} = \frac{c}{2+r}[2U - 2S - B_0 + a + \rho(1-\phi)B_0]$$

Again solving for ρ:

$$\begin{aligned} B_1 &= \overline{B} \\ &\Leftrightarrow \\ B_0 + S - U + \frac{P_{1,PF,c}|\{B_1 = \overline{B}\}}{c} &= \overline{B} \\ &\Leftrightarrow \\ \rho &= \frac{(1+r)B_0 - (2+r)\overline{B} + a - r(U-S)}{(1+r+\phi)B_0} = \rho_{2,PF,c} \end{aligned}$$

This is ρ_2 in Figure 9. Analoguously, it is possible to determine the other thresholds:

$$\rho_{3,PF,c} = \frac{(1+r)B_0 - (2+r)\underline{B} + a - r(U-S)}{(1+r+\phi)B_0}$$
$$\rho_{4,PF,c} = \frac{(1+r)B_0 - (2+r)\underline{B} + a - r(U-S) - (1-\phi)I}{(1+r+\phi)B_0}$$
$$\bar{\rho}_{PF,c} = \frac{(1+r)B_0 + a - r(U-S)}{(1+r+\phi)B_0}$$

Some questions in terms of relationships between the different threshold levels come to mind: Could it be that $\rho_{1,PF,c} > \bar{\rho}_{PF,c}$?

- No, because at $\bar{\rho}_{PF,c}$, $B_1 = 0$ and for all intake rates smaller than that $B_1 > 0$. There is no overlap.

Could it be that $\rho_{3,PF,c} > \bar{\rho}_{PF,c}$?

- As $\underline{B}$ gets closer to 0, $\rho_{3,PF,c}$ gets closer to $\bar{\rho}_{PF,c}$, but as long as $\underline{B} > 0$, the answer is no.

Could it be that $\rho_{4,PF,c} > \rho_{3,PF,c}$?

- Yes, this happens if the thresholds for the aggregate private bank and thus reserve interactions are smaller than the value of injections, i.e. $\overline{B} - \underline{B} \leq \frac{1-\phi}{2+r} I$.

Is $\rho_{4,PF,c}$ always smaller than $\rho_{3,PF,c}$?

- Yes, because we find that after subtraction, the condition $-(1-\phi) < 0$ is true.

Is $\rho_{1,PF,c}$ always larger than $\rho_{2,PF,c}$?

- Yes, because we find after substraction that $-(1-\phi)\overline{B} < 0$ is true.

What happens if $I > \rho(B_0 + B_1)$?

- In that case the reserve would create allowances from nothing. In the model, we make sure that this doesn't complicate the results for small values of ρ by assuring at all times that $\rho_{4,PF,c} B_0 > I$, which is the minimal requirement for injections to always be covered by allowances in the reserve.

Hence, we can define a minimal path of FCCs independent of ϕ whith reserve regime switches at $\rho_{2,PF,c}$ and $\rho_{3,PF,c}$. Where there is overlap, the lower path implies a Pareto improvement relative to the higher one.