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The Reformed EU ETS in Times of Economic Crises: the Case of the COVID-19 Pandemic[⋆]

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Abstract

To tackle structural supply-demand imbalances and to increase price stability in times of economic crises, policy makers reformed the European Union Emission Trading System (EU ETS) substantially in 2015 and 2018. As the COVID-19 pandemic led to an unforeseen contraction of the economy, it serves as an example to evaluate if the reforms can live up these goals. The paper at hand uses a partial equilibrium model that depicts current EU ETS regulation to determine the impact of the pandemic on allowance prices and emissions the EU ETS. The results indicate that due to the Market Stability Reserve (MSR) and the Cancellation Mechanism, the Corona crisis reduces aggregate emissions in the EU ETS. This finding holds even if the crisis is followed by an economic rebound in the same or larger magnitude than the initial recession. Further, the new regulation increases the robustness of the ETS towards economic shocks as the reforms increase the relative price stability in the market. While these findings hold for the COVID-19 pandemic, the results can yet not be generalized to a generic economic crisis since they strongly depend on the shape, size and timing of the exogenous shock.

Keywords: Dynamic Optimization, EU ETS, COVID-19, Market Stability Reserve, Economic Shock

JEL Classification: D25, D91, H32, Q58

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1. Introduction

Since January 2020, COVID-19, also referred to as Corona virus, is changing people's everyday lives all around the globe. The repercussions of the pandemic are observable on the stock and commodity markets worldwide.[1] Lower industrial production and declining power generation decreased CO_2 emissions in the short run.
Studies analyzing the impact of COVID-19 on energy demand in the United States (U.S.), for example, point out that the Corona crisis will likely cause a temporary deferral of production that is followed by a rebound in economic activity (see e.g. Gillingham et al. (2020) and Ou et al. (2020)). Emissions will therefore only be reduced in the short run, while aggregate emissions will not change or even increase due to a rebound effect that may surpass the emission reduction caused by the economic shock (Gillingham et al., 2020). Such a temporal shifting of emissions may occur not only in the U.S. but in many regions of the world. However, the effect is not so clear when looking at emissions in the European Union, as emissions from energy-intense industry, the electricity sector and inner-European aviation are capped by the European Union Emission Trading System (EU ETS).
Since 2005, the EU ETS accounts for more than 45% of emissions in the EU, United Kingdom, Liechtenstein, Iceland and Norway, making it the most prominent instrument of European climate change policy. For every tonne of CO_2 equivalent (CO_2e) emitted within the EU ETS sectors, the emitting firm needs to surrender a certificate. Those certificates - called EU allowances (EUA) - can be traded between firms, efficiently coordinating abatement to firms with low abatement costs and allowances to firms with high abatement costs.

The 2008 and 2009 financial crisis posed some challenges to the modus operandi of the EU ETS: as the recession caused fewer emissions and therefore low allowance demand, firms were able to save a significant number of EUA. This not only led to low allowance prices during the recession years - and reduced the incentives to invest into low-carbon technology (Bel and Joseph, 2015) - but also caused the build-up of a large stock of allowances. Thus, the economic crisis did not cause overall emissions in the EU ETS sectors to decrease, as firms simply stored unused allowances for future usage.
Given this experience, the EU ETS has been substantially reformed: In 2014, the European Commission decided to postpone the auctioning of 900 million EUA (referred to as "backloading") to temporarily tighten the allowance supply (European Commission, 2014a). One

[1] The International Monetary Fund (IMF), for example, estimates that the global economy could contract by 4.9% alone in 2020 (IMF, 2020).

year later, the so called Market Stability Reserve (MSR) was established. The MSR became operational in 2019 and serves as a public allowance reserve where part of the annual allowance supply is deposited whenever the private allowance bank held by firms in the market - called the Total Number of Allowances in Circulation (TNAC) - exceeds a certain upper threshold. Allowances from the MSR are returned to the market when the TNAC falls under a lower threshold. (European Parliament and the Council of the European Union, 2015).
In 2018, policy makers increased the linear reduction factor (LRF) for the annual allowance supply from 1.74% in the third trading period (2013-2020) to 2.2% from 2021 onwards, tightening the emission cap in the long run. Further, the MSR regulation was amended through a Cancellation Mechanism that will become operational in 2023 (European Parliament and the Council of the European Union, 2018). Whenever the number of allowances stored in the MSR exceeds the total allowance supply of the previous year, the respective excess allowances are rendered invalid. The MSR and the Cancellation Mechanism therefore changed the modus operandi of the EU ETS fundamentally, as cumulative emissions are no longer just exogenously determined through the allowances supplied by the policy maker but partly endogenously determined by the banking decision of firms (Bocklet et al., 2019). The underlying goal of the European Commission was to reform the EU ETS so that it is more resilient towards structural supply-demand imbalances in times of economic crises. Further, the MSR and Cancellation Mechanism should ensure price stability and price predictability (European Commission, 2014b). The reformed EU ETS thus aims to deliver "the necessary investment signal to reduce CO_2 emissions in a cost-efficient manner" (European Parliament and the Council of the European Union, 2015).

To analyze the impact of an unforeseen economic shock on the EU ETS, the paper at hand uses an intertemporal emission trading model that accurately depicts the recent reforms. The model assumes a perfectly competitive market, where firms minimize costs of emission trading through emission abating and allowance trading. Firms are assumed to be myopic and risk-avers, i.e. they have a limited planning horizon and are obliged to exogenous hedging requirements to mitigate price risk. The model hereby directly builds on the model developed in Bocklet and Hintermayer (2020). In addition to previous intertemporal emission trading models (as e.g. used in Chevallier (2012), Perino and Willner (2016), Quemin and Trotignon (2018) and Bocklet et al. (2019)), an unforeseen economic crisis is implemented into the model as a demand-reducing, exogenous shock to baseline emissions.[2]

[2]Baseline emissions are defined as emissions in the absence of an emission trading system.

In the first part of the analysis, I discuss the theoretical implications of a generic, unforeseen demand-reducing exogenous shock on market outcomes in the reformed EU ETS. The analysis builds on a strand of literature that evaluates the interplay of the EU ETS reforms and demand-reducing complementary policies (e.g. Rosendahl (2019), Schmidt (2020), Beck and Kruse-Andersen (2020) and Herweg (2020)). In line with these studies, I find that the long-run impact of a short-run demand reduction strongly depends on its timing and its magnitude. An economic crisis that happens within the third trading period decreases aggregate emissions more than a crisis that happens at a later point in time. Further, a deep and short economic crisis reduces aggregate emissions relatively more than a shallow crisis that lasts for longer period of time.
In a second step, the model described above is used to quantify the impact of the COVID-19 crisis on key variables in the EU ETS. As the COVID-19 crisis was not foreseen by market participants ex-ante, firm's expectation on baseline emission before 2020 deviate from the realized baseline emissions in 2020 and possibly also for the following years. The numerical results on aggregate emissions and EUA prices are used to discuss if the regulatory framework, especially the MSR and the Cancellation Mechanism, can live up to its promises by reducing structural supply-demand imbalances and increasing price stability in the market. The impact of the COVID-19 pandemic on prices and emissions in the EU ETS has so far only been discussed by Azarova and Mier (2020) and Gerlagh et al. (2020). Using three different scenarios, Azarova and Mier (2020) find that the longer the pandemic, the larger cancellation volumes and the lower aggregate emissions. While Azarova and Mier (2020) determine MSR and cancellation volumes iteratively within a model of the European electricity market, the intertemporal emission trading model used within the paper at hand is able to retrieve the respective volumes endogenously. Thereby, the modelling rather resembles the approach used in Gerlagh et al. (2020) who evaluate the impact of the COVID-19 crisis on absolute EUA prices. They find that the MSR reform is able to stabilize prices in light of the Corona crisis to some extent. The MSR mechanism is found to be most effective in stabilizing prices when firms expect the COVID-19 crisis to be severe but temporary. While Gerlagh et al. (2020) compare absolute prices of the regulatory framework today with absolute price in absence of the MSR mechanism and assume that firms have perfect foresight, the paper at hand differs from their approach as it acknowledges that firms are shortsighted. Further, an indicator of relative price stability - measuring the relative distance of realized prices to expected prices - is used to compare price stability in the pre- and post-reform market.

Additionally, I investigate the impact of the pandemic on aggregate emissions in the ETS using five different crisis' scenarios.
The findings on the impact of the COVID-19 crisis on market outcomes of the EU ETS are threefold:
First, if firms expect long-run baseline emissions to be lower, the Corona crisis reduces short-run prices in 2020 compared to the no-shock price trajectory.
Second, COVID-19 reduces aggregate realized emissions in the EU ETS as the short-run emission reduction translates into a larger private allowance bank and triggers additional allowance cancellations. The numerical results show that the size of the additional cancellation ranges from 12 Mt CO_2e to 19 Mt CO_2e. Depending on the size and the shape of the initial shock, between 1%-52% of the short-run emissions that are saved during the COVID-19 crisis will therefore also be reduced in the long run. The findings remain valid even if the economic rebound following a recession is larger than the recession itself. Relative cancellation volumes are largest, when the COVID-19 shock is short. The longer the crisis persist, the less powerful the MSR mechanism. If the ETS reforms mitigate structural supply-demand imbalances and to what extend therefore strongly depends on the nature and development of the crisis.
Third, by comparing the market outcomes resulting from the Corona crisis of the pre-reform scenarios (in the absence of the current MSR and Cancellation Mechanism) with the results of the post-reform scenarios, I find that the reforms decrease price volatility and increase price stability during the planning horizon of a firm for all scenarios. The numerical findings in light of the COVID-19 pandemic therefore suggest that the MSR is indeed able to fulfill its initial goal to increase price consistency in times of an economic crisis.

The remainder of the paper is organized as follows: In Section 2, an intertemporal optimization model of the EU ETS is set up based on post-reform regulation. Further, the economic shock is implemented into the model as a deviation of realized baseline emissions from expected baseline emissions. In Section 3, the theoretical implications of a generic economic shock are discussed and embedded into the literature. Section 4 analyses the impact of the COVID-19 pandemic on numerical outcomes in the EU ETS. To do so, the model is parameterized (Section 4.1) and different shock scenarios are introduced (Section 4.2). The numerical result are shown in Section 4.3. In Section 5, the current policy framework is evaluated by analyzing the impact of the COVID-19 crisis on aggregate emissions and the market's price responds towards the economic shock. As the numerical results strongly depend on the underlying parameter assumption, they are validated by sensitivity analyses (Section 6). Section 7 concludes.

2. The Model

In the following, a partial equilibrium model of the EU ETS is set up. The allowance market is assumed to be perfectly competitive and to consist of N homogeneous firms. It can be seen as an extended, discrete-time version of the seminal model developed by Rubin (1996) which has previously been applied to the EU ETS at its different reform stages by Chevallier (2012), Perino and Willner (2016) and Bocklet et al. (2019), among others.
While the aforementioned papers assume that firms are perfectly rational, the European Commission points out that firms typically have a limited planning horizon and hedge themselves to mitigate price risk (European Commission, 2014a). Both forms of bounded rationality have also been subject of discussion in the literature: Salant (2016) and Edenhofer et al. (2017), for example, argue that firms are either incapable or unwilling to consider the future until infinity. Contrarily, firms are likely short-sighted and only incorporate a limited time horizon into their decision making. Further, as firms are risk-avers (Kollenberg and Taschini (2019) and Schopp and Neuhoff (2013)) firms are likely prone to exogenous hedging requirements that may exceed the endogenously derived banking decisions (Bocklet and Hintermayer, 2020). The reason behind this is that power producers - as one of the largest emitters in the EU ETS - have limited potential to shift their portfolio to low-carbon production in the short run. In order to balance the carbon price risk, they hedge their future power sales.
Thus, the model used throughout this paper accounts for myopia and exogenous hedging requirements and hereby closely resembles the model developed in Bocklet and Hintermayer (2020).

2.1. The Firm's Optimization Problem

In the following, the optimization problem of a representative firm is set up for the no-shock scenario. Since the market consist of homogeneous firms, the market demand is derived by the aggregated choice of all firms in the market. I assume that in this setting, the firm has perfect information on the economic development within its planning horizon, so that the regulatory framework is foreseen ex-ante within this planning horizon and expected baseline emissions equal realized baseline emissions. This scenario therefore depicts the firm's

expectation on the economic development before an exogenous shock as e.g. an economic crisis occurs.
Formally, a firm solves the intertemporal cost minimization problem $\mathcal{M}(\tau, \mathcal{H})$

$$
\begin{aligned}
\min \quad & \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}[C(e(t)) + p(t)x(t)] \\
& \qquad s.t.\ b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = \tau, \tau+1, \ldots, \tau+H \\
b(t) \geq \quad & \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t} - t) \cdot e(\tilde{t}), \\
& \qquad x(t),\, e(t) \gtrless 0.
\end{aligned}
\tag{1}
$$

The firm's objective is to minimize the discounted costs for abatement $C(e(t))$ and allowance trading $p(t)x(t)$. Discounting is depicted by the interest rate r. The abatement cost function is assumed to be quadratic and convex[3], i.e. $C(e(t)) := \frac{c(t)}{2}(u(t)) - e(t))^2$ with the cost parameter $c(t)$, baseline emissions in year t $u(t)$ and the firm's decision on annual emissions $e(t)$. While the allowance price $p(t)$ is determined on the market level and therefore exogenous in the firm's decision problem, the firm decides on net allowance purchases. If these net purchases $x(t)$ exceed the emissions $e(t)$, the firm can store the allowances in a private bank for future use. This banking decision is depicted by the decision variable $b(t)$.

As all firms are assumed to be risk avers, firms need to fulfill exogenous hedging requirements. Thus, their banking decision $b(t)$ is bound to the hedging requirement $hedgeshare(\tilde{t}-t)e(t) \geq 0$ that determines a minimum requirement on allowances to be banked in t for emissions in a future period $\tilde{t}$.
Beside these hedging needs, firms deviate from the assumption of perfect rationality further as they are incapable to consider the infinite future. I thus follow Willner (2018), Quemin and Trotignon (2019) and Bocklet and Hintermayer (2020) by incorporating myopia into the decision making of the firm. In every year τ the representative firm decides on emissions $e(t)$, banking $b(t)$ and net allowance sales for the next H years. While the firm disregards

[3] While Schmidt (2020) scales the slope of the MAC in order to present various curvatures, Herweg (2020) proves that results hold as long as the MAC are not too convex. As MAC are convex but flatten over time, this assumption applies for the model as it accounts for a time span until 2100. The assumption of quadratic MAC is therefore sufficient and used throughout this paper, as also assumed in Perino and Willner (2016) and Bocklet et al. (2019)

any information beyond this time horizon, information becomes available to the firm as time unfolds through a rolling horizon approach.

From Equation 1, the corresponding Lagrangian is derived (see Appendix A) by assigning Lagrange multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow and hedging constraints, respectively. As the optimization problem fulfills the Slater conditions and is convex, the Karush-Kuhn Tucker (KKT) conditions are sufficient to derive the following optimality conditions:

$$c(t)[u(t) - e(t)] = p(t). \tag{2}$$

This implies that at every time t, marginal abatement costs are equal to market prices. As firms in the market are assumed to be homogeneous, one can also derive the amended Hotelling price rule from the individual equilibrium conditions, namely

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1}\frac{\mu_b(t)}{p(t)}. \tag{3}$$

Whenever the hedging constraint is not binding, i.e. $b(t) > \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t} - t)e(\tilde{t})$, $\mu_b(t) = 0$ so that prices increase with the interest rate.[4] Once the hedging requirement binds, prices can deviate from the Hotelling rule and may therefore increase at a lower rate.[5]

2.2. Regulatory Rules and Market Equilibrium

On the market level, prices $p(t)$ are determined so that aggregated emissions over time are smaller than the aggregated allowance supply, i.e. $\sum_{\tilde{t}=0}^{t} e(\tilde{t}) \leq \sum_{\tilde{t}=0}^{t} S(\tilde{t})$ for all $t = 0, 1, \ldots, T$.

Allowances are issued annually, referred to as $S(t)$. 57% of these allowances are auctioned (S_{auct}) while the other part is issued for free (S_{free}) via benchmarking. Due to the MSR and the introduction of the Cancellation Mechanism, the allowance supply is no longer just exogenously given but partly determined by the aggregate banking behavior of the firms in the market. It can be stated as:

$$S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct} - MSR_{Intake}(t) + MSR_{Reinjection}(t). \tag{4}$$

[4]See Hotelling (1931) for a concise explanation.

[5]If firms are myopic and have large hedging requirements, and allowances are scarce due to the restricted annual supply, prices may even decrease (Bocklet and Hintermayer, 2020).

The parameter $a(t)$ hereby presents the annual linear reduction factor (LRF) that ensures that allowance supply is reduced over time from the initial allowance supply S^0_{auct}.[6]

If the TNAC[7] - representing the aggregate allowance bank of all firms in the market - exceeds the threshold $\ell_{up} = 833$ million EUA, a share $\gamma(t) = 24\%$ of allowances is withheld from the auction and put into the MSR, referred to as MSR_{Intake}.[8] If the TNAC falls below the threshold $\ell_{low} = 400$ million EUA, tranches of $R = 100$ million EUA are reinjected from the MSR into the auction, referred to as $MSR_{Reinjection}$.
Formally, this is described by

$$MSR_{Intake}(t) = \begin{cases} \gamma(t) \cdot TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else}, \end{cases} \tag{5}$$

and

$$MSR_{Reinjection}(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else}. \end{cases} \tag{6}$$

Whenever the aggregate MSR volume $MSR(t) = MSR(t-1) + MSR_{Intake}(t) - MSR_{Reinjection}(t) - Cancel(t)$ exceeds the previous year's auction volume, the auction supply of the following year is reduced, such that

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise}. \end{cases} \tag{7}$$

Since the MSR and the Cancellation Mechanism are precisely embedded into the partial equilibrium model, I am able to retrieve a closed-form solution, including endogenous MSR and cancellation volumes.

[6]The initial auction supply S^0_{auct} in 2010 was 2199 million and declines with a LRF $a(t)$ of 1.74% until 2020, and with 2.2% afterwards.

[7]Based on the first publication of the TNAC, the TNAC of 2017 (1645 million EUA) is used to parameterize the model (European Commission, 2018b)

[8]From 2024 onwards, this share will be reduced to 12%.

2.3. Post-Shock Model

In contrast to the no-shock model, the post-shock model incorporates an external shock on baseline emissions which was not foreseen ex ante by market participants. During the shock year(s) t_{shock}, realized baseline emissions $\hat{u}(t_{shock})$ deviate from expected baseline emissions $u(t_{shock})$. As the length of the economic shock varies depending on the nature of the crisis, t_{shock} can take different values, ranging from a shock that is limited to one year only, over a shock that lasts multiple years to an economy where baseline emissions always remain at a lower level than in the no-shock scenario.

While the cost minimization problem of the firm (Equation 1) and the regulatory rules described in the no-shock scenario remain unchanged, the realized baseline emissions $\hat{u}(t_{shock})$ update the cost parameter so that $\hat{c}(t_{shock}) = \frac{BC}{\hat{u}(t_{shock})}$. Due to the assumption that an exogenous shock does not alter backstop costs, the change in marginal abatement costs leads to a change in market outcomes.

3. Theoretical Considerations and Relevant Literature

With the introduction of the MSR and the Cancellation Mechanism, the allowance supply in the EU ETS becomes partially endogenous. An exogenous shock that impacts allowance demand in the short run might therefore also impact market outcomes in the long run. As an economic crisis reduces the baseline emissions so that $\hat{u}(t_{shock}) < u(t_{shock})$, allowance demand decreases during this time. Instead of using allowances to cover emissions, firms bank unused allowances for the future. As the aggregate allowance bank determines the size of the MSR (see Equations 5 and6), a larger TNAC may increase the MSR intake volume (or decrease the reinjection from the MSR to the market). In case the MSR volume exceeds the previous year's auction volumes, excess allowances are cancelled. Thus, an economic crisis today can lead to lower aggregate emissions under the current regulatory framework. However, due to the complex endogenous supply rules (see Section 2), it is not possible to analyze the effect on market outcomes for a generic crisis. Contrarily, the impact of an economic crisis on aggregate emissions strongly depends on the specifications of the crisis. In the following, I analyze stylized effects for different types of crises and embed those theoretical considerations into the literature. In particular, the following determinants are used to differentiate the diverse effects of a crisis on market outcomes in the EU ETS: timing, size and length of a crisis.

In order to understand why timing of the crisis determines its long-run impact, a closer look at the current regulatory framework is needed:
In addition to the endogenous MSR intake mechanism stated in Equation 5, the MSR was initially endowed with 900 million backloaded allowances. Approximately 600 million allowances that remain unallocated by the end of the third trading period will additionally be inserted into the MSR by the end of 2020. As the TNAC volumes in 2019 amounts to 1654 million allowances, it exceeds the threshold of 833 million allowances. Therefore, roughly 400 million allowances are additionally transferred into the MSR in 2020. Thus, today's MSR volume already exceeds the auction supply in 2022 (roughly 1700 million allowances), indicating that the Cancellation Mechanism will be triggered once it becomes operational in 2023.[9] Hence, as long as the TNAC remains at a level of more than 833 million allowances, any demand-reducing economic crisis that happens before 2022 will automatically trigger additional cancellation volumes and thereby reduces aggregate emissions. This holds irrespective of the severity of the crisis. However, based on the MSR intake share, up to 24% of the yearly emission reduction caused by the crisis will be cancelled via the Cancellation Mechanism.
If an economic crisis happens after 2022, the impact on aggregate emissions strongly depends on the size of the demand reduction: First, after 2020, the MSR volume only changes based on the endogenous intake rules. Thus, after the initial cancellation of allowances in 2023, the MSR volumes remain significantly smaller than in the third trading period when backloaded and unallocated allowances are additionally inserted into the MSR. Second, the endogenous MSR intake will likely decrease over time. Since the allowance supply is annually reduced by the policy maker, scarcity increases and banking decreases over time. Thus, eventually, the TNAC will be so small that no further allowances will be transferred into the MSR. Beck and Kruse-Andersen (2020) refer to this point in time as cut-off date. In order to impact long-run emissions, a crisis would thus need to be so severe, that it increases the TNAC in way, that the the cut-off date is postponed and the MSR volumes is increased so much that the Cancellation Mechanism is triggered in the following year(s).[10]

[9] Literature evaluating the ETS in absence of a crisis suggests that the initial cancellation in 2023 ranges from 1700 million allowances (Perino and Willner, 2017) over 2000 million allowances (Bocklet et al., 2019) to 3000 million allowances in Beck and Kruse-Andersen (2020).

[10] Note that even if such a severe crisis takes place, the absolute impact of such a crisis after 2022 is smaller than the impact of an early crisis, as only 12% of the TNAC are inserted in the MSR after 2023, instead of 24%.

Consequently, a shallow crisis taking place after 2022 will have no effect on aggregate emissions at all. The short-run reduction of baseline emissions will simply translate into higher emissions in the long-run, leaving aggregate realized emissions unchanged. This phenomenon is often referred to as temporal waterbed effect.

These considerations are in line with the findings of numerical analyses provided by Carlen et al. (2018) and Beck and Kruse-Andersen (2020). While the respective papers analyze the impact of overlapping policies on market outcomes in the reformed EU ETS, the findings are transferable to an economic crisis if one only considers national policies that reduce allowance demand (e.g. a national coal phase out). Carlen et al. (2018) find that emission reductions early on are always better than those that occur later. A temporary generic overlapping policy that reduces 1 Mt CO_2e in 2019, for example, reduces long-run emissions by 0.81 million (Carlen et al., 2018). The Cancellation Mechanism therefore substantially reduces the waterbed effect. A similar result is found by Beck and Kruse-Andersen (2020) who evaluate a policy that reduces 10 million allowances over the course of 10 years. They find that 8 million of those allowances are deleted via the Cancellation Mechanism. Contrarily, if the demand reduction happens after the MSR intake stops, i.e. when the allowances supplied to the market are scarce and banking is no longer feasible, demand reducing overlapping policies do not affect long-run emissions. The later a policy is implemented, the larger the waterbed effect. Eventually, the waterbed effect is fully restored, just like in the case of a small economic crisis that happens after 2022.

The numerical results described above show that not only the timing and the severity of a demand reduction determines the size of the waterbed effect, but also the length of the demand reduction. Hereby, one can differentiate between a temporary crisis, where allowance demand eventually returns to its pre-shock level, and a permanent crisis that causes lower baseline emissions at any point in time. A temporary crisis that e.g. only last for one year mitigates the waterbed effect most, as the shock has not at all been incorporate into the decision making of the firms, leading to relatively large banking, MSR intake and cancellation volumes. The longer the crisis lasts, the larger the remaining waterbed effect as firms start to incorporate the lower baseline emission into their decision making once they acknowledge the crisis. The phenomenon that the waterbed effect increases with the anticipation time is often referred to as "anticipation effect".

Most prominent in the academic literature is the dispute about this anticipation effect between Perino (2018) and Rosendahl (2019) who both evaluate the effectiveness of permanent, demand reducing overlapping national policies in light of the new EU ETS regulation. The

key question is, if a short-run emission reduction translates into lower aggregate emissions or if overall emissions remain the same or even increase as firms store unused allowances for future usage. Using a static setting of the EU ETS, Perino (2018) finds that the MSR and the Cancellation Mechanism can reduce the waterbed effect if a national policy increases the MSR intake. If this finding holds, strongly depends on the timing of implementation. Similar to the numerical result on the effect of a temporary demand reduction shown by Beck and Kruse-Andersen (2020) and Carlen et al. (2018), Perino and Willner (2016) find that overlapping policies implemented early on may reduce the waterbed effect by up to 80%. Policies that are implemented after 2025, do not reduce emissions at all. In contrast to those findings, Rosendahl (2019) claims that these papers do not take the anticipation effect into account. As firms anticipate lower demand in the future, prices decrease and emissions increase in the short run. This might even lead to higher absolute emissions in the long run, a phenomenon coined by Rosendahl (2019) as the "new green paradox".
While the ambivalent results in the literature mainly stem from the question when firms acknowledge policy changes and the corresponding reduction in future demand, this question is not relevant when analyzing the effect of an unforeseen demand shock such as an economic crisis. Yet, the length of the crisis determines if firms can incorporate the lower baseline emissions into their decision making or not. A crisis that is expected to last multiple years increases the anticipation time and thereby restores the waterbed effect to some extent.

Due to the changing policy framework and the complexity of the endogenous allowance supply, it is not possible to determine the effect of a generic economic crisis on market outcomes in the reformed EU ETS. The impact of an exogenous shock on aggregate emissions strongly depends on the timing, the size and the length of an economic crisis.
Yet, from the theoretical considerations discussed above, the following stylized conclusions can be drawn:
An early economic crisis decreases aggregate emissions more than a crisis that occurs later on.
A crisis that reduces allowance demand strongly leads to relatively lower aggregate emissions than a shallow crisis.
Therefore, it can be concluded that a short and severe crisis at an early point in time lowers aggregate emissions most. Contrarily, a crisis that reduces annual baseline emissions little, lasts for a long period of time and/or happens late, only changes aggregate realized emissions little, rendering the reforms ineffective.

4. The Impact of the COVID-19 Pandemic on the EU ETS

Since it is not possible to depict general effects on en economic crisis on market outcomes in the reformed EU ETS, in the following the COVID-19 crisis serves as an example to obtain numerical market results. To do so, the model set up in Section 2 is parameterized (Section 4.1). To depict the difference in the size and shape of the shock, five different post-shock scenarios are used to describe potential long-run effects of the COVID-19 crisis (Section 4.2). Given the parameterization and using these five scenarios, the model is implemented as a mixed Integer model in GAMS and solved with CPLEX. The numerical results are shown in Section 4.3.

4.1. Parameterization

Besides the regulatory parameters provided by the policy maker that are shown in Section 2, assumptions on the interest rate, the cost parameter, the hedging schedule and the planning horizon of are provided (Section 4.1.1).

As the assumption on baseline emissions is a critical component when analyzing the long-run impact of the COVID-19 pandemic numerically, a separate subsection is devoted to their calibration (Section 4.1.2).[11]

4.1.1. Exogenous Parameter Assumptions

In line with e.g. Bocklet et al. (2019), I apply an interest rate of $r = 8\%$. The interest rate reflects the profitability and hence the opportunity cost of abatement.[12]

The cost parameter $c(t)$ is determined through the price of a backstop technology such that $c(t) = \frac{BC}{u(t)}$ (Bocklet et al., 2019). In accordance with the projection of an alternative abatement option such as carbon capture and storage (see e.g. Kuramochi et al. (2012)), I assume the cost of the backstop technology to be $BC = 150$ EUR/t CO_2e.

The hedging share and the planning horizon are both set according to the assumptions made in Bocklet and Hintermayer (2020): a 80% hedging share is used, implying that 80% of power sales are hedged one year ahead, 40% two years ahead and 13% three years ahead.[13]

[11] As the underlying parameter assumption do not change the modus operandi of the model but are critical for numerical results, sensitivity analyses for the exogenous parameter assumptions is provided in Section 6.1.

[12] See Osorio et al. (2020) for a detailed overview of interest rates used in common EU ETS literature.

[13] This assumption is comparable to the hedging schedule provided by one of Europe's largest power producers (RWE AG, 2019).

Further, as firms in the EU ETS plan ahead with a "limited time horizon" (European Commission (2014a), I apply a planning horizon of $H = 10$ throughout the analysis. According to Bocklet and Hintermayer (2020), this planning horizon mimics historic market outcomes in the EU ETS best.

4.1.2. Calibration of Baseline Emissions

Baseline emissions are thought of as counterfactual emissions in the absence of the ETS. They are the main determinant of allowance demand, as high baseline emissions require more abatement efforts than low baseline emissions.[14] While baseline emissions are a driving factor of the market results, it is not possible to measure a counterfactual. Most literature uses historic sectoral emissions before the introduction of the EU ETS as proxy for baseline emissions and assume that they remain constant over time. This implies that economic growth and technological advancements balance each other out. Perino and Willner (2017) and Bocklet et al. (2019), for example, assume constant baseline emissions of 1900 Mt CO_2e and 2000 Mt CO_2e, respectively. Carlen et al. (2018) and Beck and Kruse-Andersen (2020), on the other hand, assume that baseline emissions decline over time as technological advancement (e.g. increased energy efficiency) and renewable deployment decrease baseline emissions independent of the abatement efforts enforced by the EU ETS.

The calibration of baseline emissions used throughout this paper is similar to the approach shown in Quemin and Trotignon (2018): a simplified version of the Kaya identity (Kaya, 1989) is used to construct annual counterfactual baseline emissions from 2008-2100 in absence of the EU ETS. The equation decomposes the baseline emissions into the product of three factors: economic activity, energy intensity and carbon intensity, so that

$$u(t) = \textit{economic activity index}(t) \; \cdot \; \textit{energy intensity index}(t) \; \cdot \; \textit{carbon intensity index}(t). \tag{8}$$

In line with Quemin and Trotignon (2018), the economic activity index is calibrated using the volume index of industrial production for a proxy of ETS sectors provided by Eurostat (2020). Besides the decline in economic activity during the 2009 financial crisis, the economic activity index grows over time (see Figure 1). In order to justify the application of

[14] Baseline emissions of zero would even imply that the EU ETS is no longer needed, as firms would not emit CO_2e even in absence of an ETS.

the production index ex-post, I assume that the EU ETS does not impact economic activity. As literature does not find evidence for carbon leakage (see e.g. Koch and Mama (2019)), this assumption seems reasonable. To retrieve projections on the future development of the index, the historical production index is updated with an estimate on economic growth, leading to a linear increase of the economic activity index from 2019 onwards.

The energy intensity index is calculated as the fraction of Total Final Energy Consumption (TFEC) for a proxy of ETS sectors over economic productivity. While the overall TFEC in Europe remains roughly constant between 2000 and 2017 - indicating that economic activity and technological advancements balance each other out (ODYSSEE-MURE, 2020) - the TFEC in the industrial sector declines in the respective time period mostly due efficiency gains in the respective industries (Reuter et al., 2019). As the volume index of industrial production increases, the historic energy intensity index declines (see Figure 1). Quemin and Trotignon (2018) show that energy intensity declines steeper prior to the ETS than with the ETS in place. This phenomenon is also supported by the data provided by ODYSSEE-MURE (2020) that shows that prior to the introduction of the ETS around 39% of the overall energy savings stem from savings in the industrial sector. After the EU ETS was in introduced, the share declined to 30%. Therefore, it seems reasonable to assume that the ETS does not impact the energy intensity of the EU industrial and power sectors. The ex-post construction of the index based on historic data is therefore justifiable.
For the construction of future TFEC, it is assumed that the share of primary energy consumed in the ETS sectors increases with the electrification plans of the Ten Year Network Development Plan (TYNDP) (ENTSOG and ENTSO-E, 2020). The energy intensity index is then matched to the 2020 and 2030 energy efficiency targets of the EU ETS member states. Quemin and Trotignon (2018) assume that the energy intensity index decreases linearly after the energy efficiency targets are met and thus reaches zero. This implies that economic activity and final energy consumption can be fully decoupled. As literature (e.g. Haberl et al. (2020)) suggests that resource decoupling is only possible to some extent (e.g. through structural changes and outsourcing of energy-intense industries), I deviate from this assumptions and assume that the index will plateau eventually.

Lastly, the carbon intensity index is expressed as the fraction of ETS sectoral emissions over TFEC in the absence of the ETS. For the historical carbon intensity prior to the ETS, emissions for a proxy of ETS sectors stemming from the primary energy consumption of oil, natural gas and coal are reconstructed based on the emission factors of the respective energy carriers.

From 2008 onwards, counterfactual emissions are considered as the EUA price was likely responsible for some of the fuel switching during this time. Therefore, it is assumed that the expansion of renewable energies and nuclear deployment during this time are independent of the ETS. Based on the historic linear relationship of the carbon content of the Total Primary Energy Consumption (TPEC) and CO_2-neutral energy production, the pre-ETS relationship is extrapolated to match real renewable and nuclear generation.

Future values are retrieved by matching the TPEC projections to the renewable targets and the projection on the development of the nuclear power plant fleet in the EU ETS member states. Given the ongoing deployment of renewable energies, the carbon intensity index is projected to decrease over time.

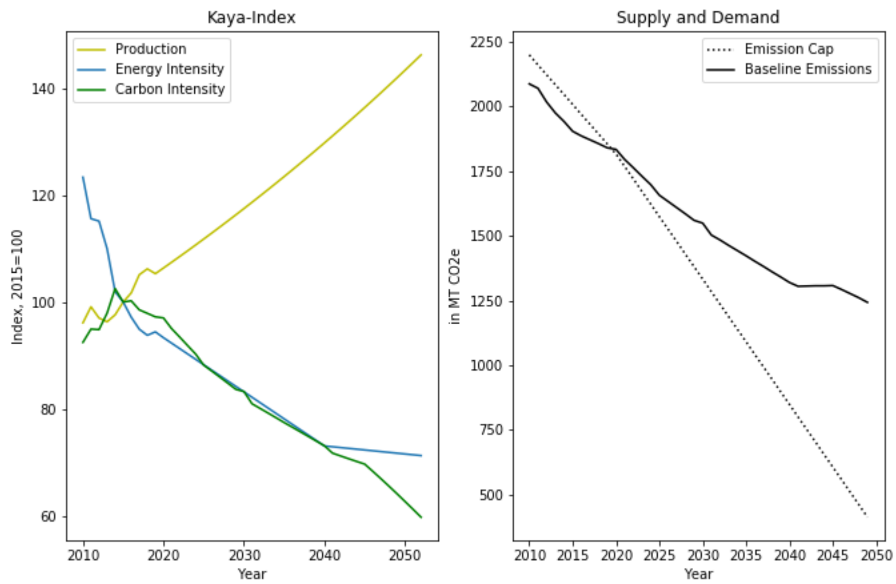

Figure 1: Kaya indices, baseline emissions and emission cap in the no-shock scenario

Figure 1 shows the projected Kaya indices, the resulting baseline emissions and the emissions cap from 2010 to 2050. The indices are normalized to 2015 values. While the economy is expected to grow over time, energy intensity and carbon intensity are projected to decline in line with EU energy efficiency and renewable deployment targets, respectively. The decline of the two Kaya factors also shows in the baseline emissions: from baseline emissions of 2080

Mt CO_2e in 2010[15] they decrease to 1340 Mt CO_2e in 2050.[16] In 2021, the emission cap becomes binding for the first time, causing allowance scarcity from 2021 onwards.

A detailed elaboration on the assumptions used for the calibration of the Kaya indices and all data sources can be found in Appendix B.

4.2. Shock Scenarios

As the precise nature of the COVID-19 induced economic downturn is unknown[17], five scenarios are used to depict likely developments of the economic crisis. The scenarios differ in their assumption on the initial reduction of greenhouse gas emissions but also assume different crisis' developments. The drop in baseline emissions used for the parametrization of the shock builds on the estimation of overall emission reduction during the COVID-19 pandemic published by Le Quéré et al. (2020). According to this publication, overall emissions in the EU fell in the first quarter of 2020 by 18 Mt CO_2e (median estimate)[18]. In order to retrieve annual greenhouse gas reductions for the ETS sectors only, I update the quarterly data to annual data and extrapolate the historic relationship between overall EU emissions and greenhouse gases emitted in the EU ETS sectors, leading to a median estimated reduction of baseline emissions in 2020 of 32 Mt CO_2e, equivalent to a 1.74% reduction in annual emissions. Note, that this estimate is substantially smaller than the short-term emission reduction of 10% assumed in Azarova and Mier (2020) and the estimate of a 260 Mt reduction assumed in Gerlagh et al. (2020). A sensitivity analysis for this assumption is therefore provided in 6.1.

A brief description on the parameter assumptions of the five shock scenarios is depicted in Table 1. t_{shock}, t_{return} and ΔU hereby indicate the year(s) of the economic shock, the year

[15] This is in the same magnitude as e.g the assumption on baseline emission of 2130 MtCO_2e used in Bocklet and Hintermayer (2020)

[16] Contrary to Quemin and Trotignon (2018), the paper at hand assumes that economic activity and resource usage cannot be fully decoupled. Further, nuclear deployment is included into the construction of the carbon intensity index and the relative share of primary energy consumed in the ETS sectors increases with the EU electrification plans. Therefore, the baseline emissions retrieved are larger than the baseline emissions shown in Quemin and Trotignon (2018).

[17] A survey by Boumans et al. (2020) conducted among industry experts in Germany, for example, reveals that only few believe that the economy will recover in 2020 already (6.7%), while 51% expect recovery in 2021 and 41.5% in 2021 or even later.

[18] The low and high estimates for this time span are 9 and 29 Mt CO_2e, respectively.

when baseline emissions in the shock scenarios return to the level of the no-shock scenario and the resulting change in aggregate baseline emissions for each scenario, respectively.

Shock Type	**Scenario Name**	t_{shock}	t_{return}	ΔU
Quick Recovery	*V-Scenario*	2020	2022	- 45 Mt
Second Wave	*W-Scenario*	2020 & 2021	2023	- 81 Mt
Slow Recovery	*U-Scenario*	2020-2025	2027	- 211 Mt
Prolonged Crisis	*L-Scenario*	2020-2100	-	- 1028 Mt
Economic Rebound	*ϑ- Scenario*	2020	2024	0 Mt

Table 1: Exogenous assumptions of the shock scenarios

In the following, the underlying economic intuition of the five shock scenarios and their parameter assumptions are described in a more detail:

Quick Recovery

Since the Corona induced economic downturn left the capital stock of firms and consumers unchanged, many economists hope for a quick recovery of the economy as soon as the pandemic is contained. Such a quick recovery depicts a best-case option where the COVID-19 pandemic can be contained by the end of 2020. This scenario can be pictured through a V-shaped economic crisis (and is therefore further referred to as $V-Scenario$).[19] After the shock, the economy is expected to reopen within a matter of several months and assumed to grow at pre-shock growth rates in 2021, returning to the pre-shock economic level in 2022. The overall decline in baseline emissions in 2020 and 2021 is 45 Mt CO_2e (median estimate).[20] From 2023 onwards, baseline emissions continue to develop just like in the pre-shock case.

Second Wave

Contrary to the former scenario, in the $W-Scenario$ it is assumed that the economy will stagnate in 2021 at the low economic levels of 2020, start to grow in 2022, returning to the

[19]This scenario closely resembles the first scenario setting assumed in Gillingham et al. (2020) and the fast-recovery scenario depicted in Azarova and Mier (2020).

[20]This decline in baseline emissions is therefore in line with the projection of (Hein et al., 2020) who estimate that emissions from industry and energy will reduce by roughly 50 tonnes of CO2e in response to the Corona crisis.

pre-reform economic level as late as 2023.[21] Such a relapse of the economic shock can be either caused by a sudden increase in case numbers and therefore a second lock-down of the European economy or by a (premature) lifting of economic support for European industry and households. The $W-Scenario$ hereby only differs from the $V-Scenario$ by the overall length of the recession.[22] Aggregate baseline emissions are estimated to decline by 81 Mt $CO2e$.

Economic Rebound

In order to account for a potential overshoot of post-shock emissions, a third scenario $\vartheta - Scenario$ is introduced. The $\vartheta - Scenario$ constitutes that overall emission remain unaltered by the crisis, as the rebound in economic activity will cause emissions levels in the aftermath of the crisis to surpass no-shock emissions in the respective years. Hereby, it is considered that the capital base in the economy remains unaltered during the crisis so that the demand for products and services is not destroyed but simply deferred to a later point in time (Gillingham et al., 2020). While the underlying assumptions on the duration of the crisis are the same as in the $V-Scenario$, baseline emissions in the aftermath of the shock are expected to increase in 2022 beyond pre-shock levels, so that aggregate baseline emissions remain the same despite the crisis. By 2024, emissions are expected to return to the no-shock trajectory path.

Slow Recovery

While all aforementioned scenarios assume that the economy will return to previous levels no later than 2024, some scholars expect that the Corona crisis will lead to a long lasting global recession in similar or even large magnitude than the financial crisis. The underlying assumption is that Corona will cause liquidations and far reaching disruptions to the European supply chain, far beyond the short-run impact of the initial economic lockdowns during the pandemic. Such a prolonged economic drop with slow recovery can be pictured through a U-shaped economic crisis, hence referred to as $U-Scenario$.[23] The $U-Scenario$ is parameterized, so that after the recession in 2020 the economy of the EU ETS countries

[21] These scenario assumptions are in line with the projections in Kissler et al. (2020).

[22] As the model only takes annual variables and yearly parameter assumptions into account, the $W-Scenario$ does not explicitly show a potential economic recovery in the second half of 2020, yet implicitly accounts for such a recovery by using the average annual growth rate.

[23] This scenario is similar to the second scenario used in Gillingham et al. (2020) and the gradual recovery scenario depicted in Azarova and Mier (2020).

stagnates from 2021 to 2025. From 2027 onwards, baseline emissions return to the pre-shock trajectory. Therefore, aggregated emissions in this scenario are estimated to be 211 Mt CO_2e lower than in the no-shock case.

Prolonged Crisis

Some scholars fear that the corona pandemic might turn into prolonged recession. Fornaro and Wolf (2020), for example, argue that the crisis might give rise to a supply-demand doom loop and therefore a persistent economic disruption far beyond the end of the pandemic. A L-shaped economic shock would therefore not be considered temporarily, but a permanent one.[24] A permanent shock does not only lead to lower baseline emissions today but to strictly lower baseline emissions in all times in the future. After a reduction of baseline emission in the same magnitude as in the $V-Scenario$ in 2020, annual baseline emissions in all following years are reduced by 16.2 Mt CO_2e (equivalent to the extrapolated value of the low estimated from Le Quéré et al. (2020)). The aggregate reduction of baseline emissions in the scenario is therefore the highest among all scenarios, leading to 1028 Mt CO_2e fewer aggregate baseline emissions.

The deviation of realized baseline emissions from expected baseline emissions for the shock scenario is depicted in Figure 2.[25]

4.3. Numerical Results

With the parameterized model, market result for the a counterfactual market without shock (referred to as "no-shock market") as well as the five post-shock scenarios are retrieved.

4.3.1. Numerical Results No-Shock Market

The results of the no-shock market on TNAC, emissions, allowance prices, the MSR and the cancellation volumes are plotted in Figure 3. The figure further shows the exogenous assumption on baseline emissions derived by the Kaya identity. As EU ETS regulation, e.g.

[24] Such a permanent shock on a global level is also reflected in Scenario 7, described in McKibbin and Fernando (2020) and is similar to the assumptions of the profound recession scenario in Azarova and Mier (2020), where industrial emissions remain 5% lower than in the pre-shock scenario until 2050.

[25] Note that Figure 2 only shows the deviation from 2018 to 2030. However, in the L-shock scenario, realized baseline emissions deviate from expected baseline emissions also further in the future.

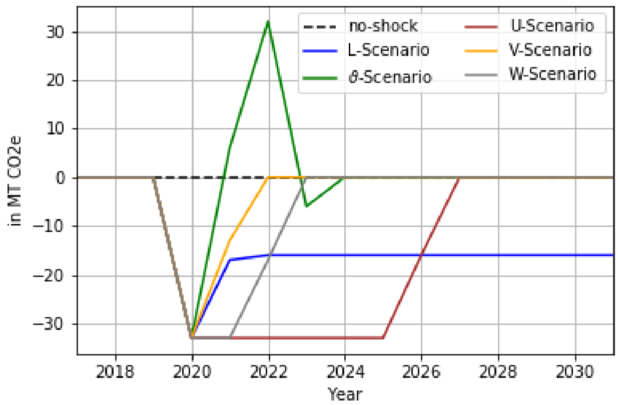

Figure 2: Difference between expected and realized baseline emissions in the shock scenarios

the LRF and the exogenous allowance supply beyond 2030 are not decided yet, I focus on the market results for the third and fourth trading period only.[26]

Due to the large hedging requirements assumed, the modeled TNAC reaches 2170 million EUA in 2018 and remains at a high level of over 1500 million EUA over the course of the third trading period. While the aggregate private bank retrieved by the model is thus slightly larger than the TNAC in the real EU ETS, the model matches well the real-world development of the TNAC: based on the latest publication of European Commission, the TNAC dropped from roughly 1700 million allowances in 2018 to 1400 million allowance in 2019, indicating a 17% drop in the aggregate banking volumes. This relative drop in the TNAC is equivalent to the development of the model results, where the TNAC volume is projected to drop from 2170 million EUA in 2018 to 1790 million EUA in 2019. The TNAC for the fourth trading period (2021-2030) is expected to remain at around 1000 Mt EUA annually.

Due to the overall large TNAC in the third and fourth trading period, large MSR intake volumes and large cancellation volumes of around 4450 Mt EUA are triggered, whereas the majority of allowances (around 3700 Mt EUA) are canceled within the fourth period.

Even though baseline emissions are assumed to slightly decrease over time, realized emissions in the no-shock scenario decrease even more as the tightening of the allowance cap induces scarcity. Therefore, the gap between expected baseline emissions and realized emissions increases over time.

[26] To avoid an end of period effect and since it is currently indisputable that the ETS will continue beyond 2030, the model is run until 2100 assuming that the regulation beyond 2030 remains unaltered.

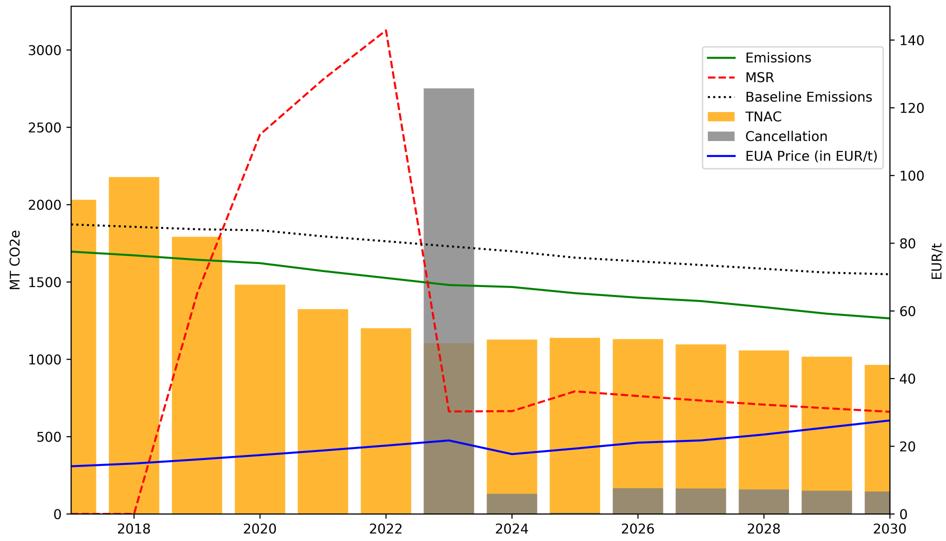

Figure 3: Realized emissions, baseline emissions, TNAC, prices and cancellation in the no-shock market

As the decrease in supply is larger than the reduction in demand, EUA prices increase over time from around 8 EUR/EUA in 2013 to 28 EUR/ EUA in 2030.[27] While the absolute price of 17 EUR/EUA in 2019 - and thus before the COVID-19 pandemic - is lower than the real ETS prices of 24 EUR/EUA visible in the market, the modeled average price between 2013 and 2019 (12.5 EUR/EUA) closely resembles the average EUA price in the respective time period of 11.7 EUR/EUA.

As firms are myopic and bound to substantial hedging requirements [28], the price development does no longer increase with the interest rate ex-post (as e.g. in Perino and Willner (2016) or Bocklet et al. (2019)) even though the Hotelling rule is applied ex-ante in the decision making of the firms. In 2023 prices even decrease, as the hedging requirements in combination with the restrictive annual allowance supply cause a temporary shortage in allowances. This shortage is resolved once supply increases as the MSR intake rate is reduced

[27]The backstop price of 150 EUR/EUA is hit in 2058, at the point of time when no more allowances are issued.

[28]See Section 6.1 for an explanation on how those assumption impact numerical results.

from 24% to 12%, depicted in a downward correction in EUA prices.[29]

4.3.2. Numerical Results of the Post-Shock Scenarios

The Corona induced economic shock changes market results significantly for all five post-shock scenarios:

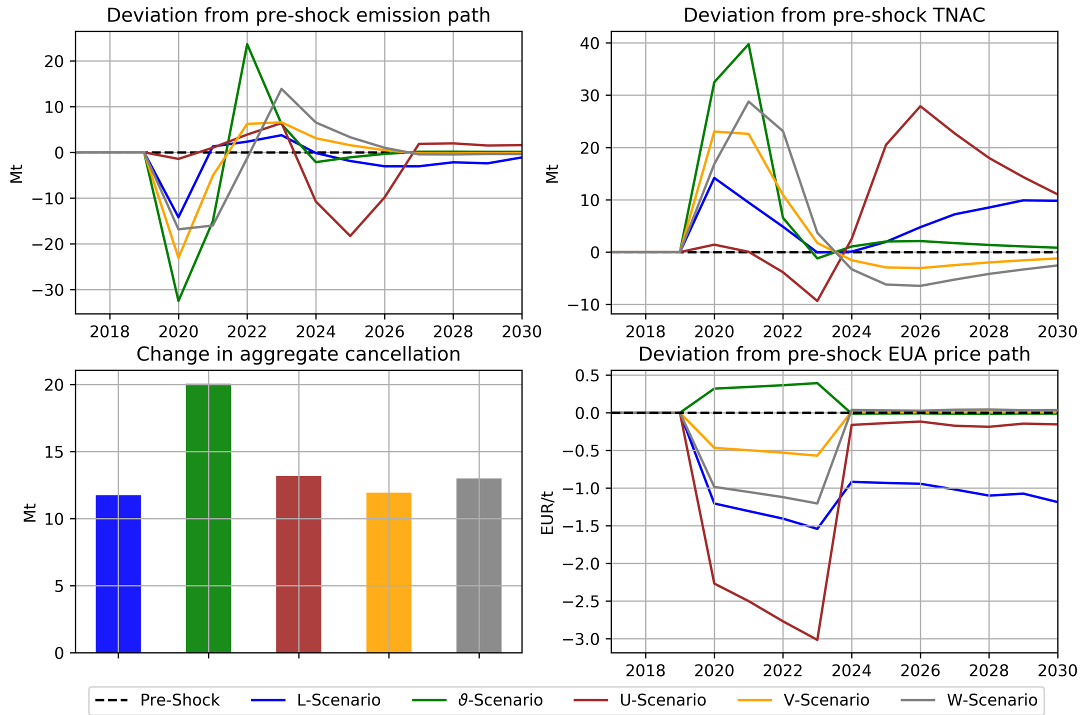

Figure 4: Changes in emissions, TNAC, cancellation volumes and prices in the shock scenarios

As firms need fewer allowances to cover their emissions in the short run (emissions in 2020 decrease between 0.1% ($U-Scenario$) and 2.0% ($\vartheta-Scenario$)), the Corona crisis increases the aggregate private allowance bank held by firms in the market. On average, Corona causes firms to increase the aggregate TNAC by approximately 110 million EUA. The increased TNAC triggers larger MSR intake and consequently larger cancellation volume for all shock scenarios and parameter values. In the described scenarios, aggregate additional cancellation

[29]See Bocklet and Hintermayer (2020) for further explanation on price corrections in response to supply shortages.

ranges from 12 million EUA in the $V - Scenario$ up to 19 million EUA in the $\vartheta - Scenario$. This is equivalent to about 1% and 1.4% of the 2020 allowance supply, respectively. Note, that for all parameter constellations, additional cancellation volumes remain strictly positive and cancellation volumes increase even above the range stated above if the rebound effect exceeds the size of the actual shock.
The increased cancellation volumes lead to fewer overall emissions: for all five shock scenarios realized aggregate emissions are strictly lower than in the no-shock scenario, implying that the Corona crisis does not only reduce short-run emissions but also decreases ETS emissions in the long run. This holds even for the rebound scenario.
While prices in 2020 decrease for most scenarios between 2.8% and 15% ($V - Scenario$ and $U - Scenario$, respectively), the expectation of a rebound effect in 2022 increases short-run prices in the $\vartheta - Scenario$. Although allowance prices deviate from the no-shock scenario in the short run, they return to no-shock levels between 2035 and 2044 for all scenarios but the prolonged crisis scenario. In the later, the post-shock allowance prices only meet no-shock prices once the backstop price is reached (2058).
Figure 4 provides an overview of the change in emissions, TNAC, cancellation volumes and allowances prices for all scenarios.

Note, that after an initial price drop of roughly 20% between February and May 2020, EUA prices in the real ETS stabilized again during the course of the year. With an average price level of 24.23 EUR/EUA in the first eleven month of 2020, annual prices are only 3% lower than in 2019 and therefore similar to the relative price drop shown in the $V - Scenario$.
The price drop visible in the market during the COVID-19 crisis is therefore significantly lower than the price drop observed during the financial crisis, where EUA prices decreased from 24 EUR/EUA in 2008 to 13 EUR/EUA in 2009 and thereby by more than 40%. Given the different magnitude in the market's response to the two crises, the following section analyses if the different reaction can be attributed to the changes in the regulatory framework, namely the introduction of the MSR and the Cancellation Mechanism.

5. Policy Evaluation

With the introduction of the MSR and the Cancellation mechanism, policy makers had two main intentions: first, the reforms should prevent a "large surplus of emission allowances [...] as a result of an [...] economic recession" because a large surplus translates into higher future emissions. Second, the reforms should ensure a "robust ETS" where prices are consistent with firms' expectations and thereby deliver a clear signal for firms to invest into low carbon technology (European Commission, 2014b). To discuss if the MSR and the Cancellation Mechanism are able to fulfill these two goals, the impact of the Corona crisis on aggregate emissions in the EU ETS is evaluated in Section 5.1. Further, in Section 5.2, I discuss if the MSR increases long-term certainty for investors by stabilizing prices in times of an economic crisis.

5.1. The Effect of the COVID-19 Crisis on Aggregate Emissions

To evaluate the relative degree to which the Corona crisis triggers additional cancellation and hereby reduces aggregate emissions in the EU ETS, the emission reduction indicator (ERI) is introduced. I hereby build on the methodology proposed in Schmidt (2020) who assesses the effectiveness of a demand-reducing overlapping policy based on its ability to avoid the waterbed effect. The ERI reflects the share of additional cancellation ($\Delta Cancel$) with regards to the aggregate change in baseline emissions (ΔU), i.e.

$$ERI = |\frac{\Delta Cancel}{\Delta U}|. \tag{9}$$

An ERI of 0% indicates that the crisis does not alter aggregate emissions at all, while an ERI of 100% reflects a case where every ton of CO_2e reduced during the Corona crisis is also avoided in the long run.

Scenario	ΔU	$\Delta Cancel$	ERI
V-Scenario	- 45	11.8	26
W-Scenario	- 81	12.7	16
U-Scenario	- 211	12.6	6
L-Scenario	- 1028	12.5	1
ϑ*- Scenario*	0	19	n/a

Table 2: Change in baseline emissions (in Mt CO_2e) additional cancellation (in million allowances) and ERI (in %) for each shock scenario

Table 2 shows the aggregate change in baseline emissions, and the resulting additional cancellation volumes and ERI for the five shock scenarios, ranging from additional cancellation volumes of 11.8 million allowances to 19 million allowances.[30]

Even though the drop in baseline emissions is largest in the $L - Scenario$, most additional cancellation takes place in the $\vartheta - Scenario$ where the aggregate baseline emissions remain unaltered by construction.[31]

While long-run emissions are reduced in all scenarios, the size of the remaining waterbed widely differs: in the $V - Scenario$ the MSR and Cancellation Mechanism reduce the allowance surplus most: 26% of the emissions that are saved during the Corona crisis, are also reduced in the long run. On the contrary, a permanent reduction of economic activity as proposed in the $L - Scenario$ decreases emissions in the short run but hardly impacts aggregate emissions at all: only 1% of the reduction in baseline emissions translates into long-run emissions' reduction. This numerical finding is in line with the intuition provided in Gerlagh et al. (2020) who state that the more persistent the COVID-19 shock, the less the MSR serves its initial goal.

The reason for the large difference in the waterbed effect stems from the different anticipation time in the scenarios: In the $V - Scenario$, long-run scarcity remains almost unchanged. However, a higher TNAC today leads to larger cancellation volumes. This is equivalent to the static effect described in Perino (2018). Contrarily, comparably lower aggregate baseline emissions in the $L - Scenario$ decrease long-run scarcity in the market. Firms anticipate the lower demand in the future and thus bank fewer allowances today. As this anticipation effect (Rosendahl, 2019) opposes the static affect which is prevalent in the $V - Scenario$, relatively fewer allowances are canceled the longer the recession lasts. These numerical findings therefore support the theoretical consideration on the length of a crisis provided in Section 3.

[30] Note, that due to different assumption on the size of the COVID-19 crisis on baseline emissions, absolute additional cancellation numbers depicted are substantially smaller than the results shown by Azarova and Mier (2020).

[31] This result counteracts the finding shown in Azarova and Mier (2020) who argue that absolute cancellation volumes increase with the length of the crisis. The reason for this is that the aforementioned paper only accounts for a limited parameter setting, where the three scenarios evaluated are fairly similar to each other in scope and timing and e.g. do not not account for a potential rebound effect of the economy. Once one accounts for a more diverse set of crises scenarios as e.g. a potential overshoot of the economy after the crisis, the causality found by Azarova and Mier (2020) is no longer valid.

Overall, the results indicate that some of the short-run emissions reduction caused by the COVID-19 crisis will also be preserved in the long run. The MSR therefore fulfills its goal to reduce the allowance surplus in time of economic crises. However, the magnitude of the reduction strongly depends on the size and the duration of the shock and the behavior of the market participants (see Section 6.1).

5.2. The Impact of the Reform on Price Stability

I now turn to the second goal of the policy maker by analyzing if the reforms are able to increase the robustness of the ETS by stabilizing prices.

One of the prominent concerns raised about the pre-reform EU ETS is its inability to appropriately respond to external shocks. As the supply of allowances in a cap-and trade market is fixed, external shocks lead to large price volatility. One argument in favor of the reforms was that the endogenous supply adjustment of the MSR mechanism is able to increase the markets robustness to external shocks. A robust ETS is hereby considered a market with stable price signals, as predictability of price developments is needed to ensure long-term investment in low-carbon technologies (European Commission, 2014b).

So far, scientific literature has not found a common measurement on how the predictability of price signals in an ETS can be measured and compared among different regulatory frameworks. Therefore, the findings depicted in the literature are rather ambivalent: On the one hand, Schopp et al. (2015) find that the MSR itself increases the inter-temporal flexibility in the market, making it more robust to exogenous demand shocks. Similarly, Fell (2016) shows that the MSR can reduce the over-allocations of allowances in the market and decrease price volatility. On the other hand, Quemin (2020) recently states that the post-reform ETS shows little resilience to demand shocks. He hereby supports the findings of Perino and Willner (2016) and Richstein et al. (2015) who argue that a supply- control mechanism similar to the MSR might even increase price volatility in the market if shocks occur while firms bank allowances. It is important to note that these previous studies refer to the MSR design prior to the introduction of the Cancellation Mechanism. In absence of the Cancellation Mechanism, the MSR simply shifts allowances to the future but is allowance preserving over time.

To analyze if the MSR alongside with the Cancellation Mechanism stabilize prices in times of an economic recession, I use an indicator of relative price stability (RPS). The RPS builds on the consistency indicator proposed by Schopp et al. (2015), which defines price consistency as the relative distance of realized prices to expected prices. As myopic firms do not consider the full range of the EU ETS time horizon, the RPS only evaluates price stability over the planning horizon of a firm, so that

$$RPS = \sum_{t=\tau}^{\tau+H} \frac{1}{H} | \frac{p_t(t_{shock}) - p_t(t_{no-shock})}{p_t(t_{shock})} |. \tag{10}$$

A low RPS indicates more stable prices, i.e. a RPS value of 0 indicates that prices are fully consistent with the firm's price expectations over time.
To evaluate if the MSR reform increases the robustness of the market by increasing relative price stability, I compare the indicator of the post-reform market to the indicator of a hypothetical pre-reform ETS.
By assumption, the pre-reform market mirrors EU ETS regulation at the beginning of the third trading period in 2013, i.e. the reforms on backloading, the MSR and the Cancellation Mechanism are not included in the model yet. This implies that Equations 5 - 7 do not hold in this setting. In this pre-reform market, the supply of allowances is solely exogenously determined by the regulator, so that Equation 4 reduces to $S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct}$.[32]

The numerical findings of the RPS for $\tau = 2020$ and $H = 10$ are depicted in Table 3. Expected prices are closest to realized prices in the $V-Scenario$. Contrary, a deep recession as depicted in the $U-Scenario$, increases price volatility and decreases price stability. Thus, the shorter the shock, the more stable prices.[33] This holds for both, the pre- and the post-reform market. However, the relative price stability in the pre-reform market is strictly lower than in the post-reform market for all scenarios. As prices in all pre-reform scenarios do not return to no-shock levels before the backstop price is reached, expected prices deviate from realized prices during the whole planning horizon of a firm. This is represented by a large RPS indicator. Contrary, in the post-reform market, prices return to the no-shock price path no later than 2044 (for all scenarios but the $L-Scenario$), so that from this point in

[32] Note that in order to compare the pre- and post-reform market, the allowance supply in the pre-reform ETS is increased by the expected number of unallocated allowances which are equally supplied to the market over the years 2013-2020.

[33] This is in line with the findings of Gerlagh et al. (2020) who show that absolute price levels are closest to pre-shock levels if the crisis is deep but temporary.

time ($t_{p-return}$) onwards, realized prices are consistent with the price expectations of firms before the reform.[34]

Scenario	Pre-Reform	Post-reform	$t_{p-Return}$
V-Scenario	5.10	1.13	2035
W-Scenario	11.12	2.47	2035
U-Scenario	18.57	6.68	2039
L-Scenario	26.31	5.95	n/a
ϑ- *Scenario*	4.29	1.83	2044

Table 3: RPS for $H = 10$ and $\tau = 2020$ in the pre- and post-reform market

The results indicate that the ETS reforms indeed decrease the price volatility within the planning horizon of a firm as additional cancellation volumes in light of the crisis increase prices beyond the pre-reform levels. The shorter and less severe the crisis, the more consistent prices with the initial expectations.
The reforms therefore fulfill the initial goal to increase the robustness of the market so that the ETS upholds an investment signal for low-carbon technologies even in times of economic crises.

6. Sensitivities and Shortcomings

The numerical results depicted and the findings shown in the policy evaluation are based on various parameter assumptions. This section elaborates how the exogenous parameter assumptions on myopia, hedging requirements and the size of the shock drive the numerical results (Section 6.1). For an extensive sensitivity analysis on backstop costs, interest rates and baseline emissions, the reader is referred to Bocklet et al. (2019). A discussion on the role of interest rates can also be found in Osorio et al. (2020) and Herweg (2020). Further, shortcomings resulting from the simplification of these assumptions are discussed (Section 6.2).

6.1. Sensitivities

The following sensitivity analyses are used to carve out the robustness of the results and discuss which stylized facts remain valid throughout all scenarios and parameter constellations.

[34] Even though firms do not know $t_{p-return}$ yet if a planning horizon of $H = 10$ is applied, the price deviation already decreases before $t_{p-return}$ is reached.

For simplicity, only the numerical results for market outcomes in the $V-Scenario$ are shown. However, the general trends described remain valid also for all other shock scenarios.

6.1.1. Size of the Shock

As there is high uncertainty about the severity of the shock, the following sensitivities are provided for an emission reductions of 16.06 Mt CO_2e and 52.21 Mt CO_2e in 2020, corresponding to the scaled version of the low and high estimate provided in Le Quéré et al. (2020).

With the low estimate, the total drop in baseline emissions in the $V-Scenario$ equals 21 Mt CO_2e (compared to 45 Mt CO_2e in the base case)[35]. For the high estimate, overall baseline emissions are reduced by 75 Mt CO_2e.[36] In accordance with economic theory, the market results show that the stronger the emission reductions caused by the COVID-19 crisis, the stronger prices respond to the economic shock. E.g. with the high estimate, prices between the no-shock and shock scenario fall by 4.5%. In contrast, the low estimate only reduces prices by 1.1.% in 2020.

With the severity of the shock cancellation volumes increase, implying lower aggregate emissions.[37] On the contrary, if the short-run emissions reduction of the Corona crisis is rather low (i.e. low estimate), relatively fewer emissions will also be saved in the future (ERI=19%).

6.1.2. Myopia

Since planning horizons of firms widely vary among industry, firms size and ownership structure (Edenhofer et al., 2017), it is essential to take the uncertainty regarding this parameter assumption into account. While the choice of the planning horizon does not alter the modus operandi of the EU ETS, it impacts the numerical results (Bocklet and Hintermayer, 2020). Therefore, the numerical findings provided in Section 4.3 for a planning horizon of 10 years are compared with a shorter planning horizon of 3 years and a longer planning horizon of 15 years corresponding to the potential planning horizons of small or medium sized manufacturing firms (Stonehouse and Pemberton, 2002) and a large publicly traded manufacturing firms (Souder et al., 2016), respectively.

[35] The corresponding reductions for the low estimate are 41, 0, 105 and 1012 Mt CO_2e in the W-, $\vartheta-$, U- and L-scenario, respectively.

[36] The corresponding reductions for the high estimate are 131, 0, 340 and 1048 Mt CO_2e in the W-, $\vartheta-$, U- and L-scenario, respectively.

[37] This is also in line with the findings in Schmidt (2020) who shows that larger overlapping policies lead to larger cancellations.

Assuming a shorter (longer) planning horizon than in the base case leads to lower (higher) prices in the beginning of the third trading period, as the large TNAC held by firms in the market can cover most baseline emissions during the respective planning horizon. As firms are not able to foresee the future development of the economic crisis, a short planning horizon also implies that the Corona induced price drop in 2020 is lager, the shorter the planning horizon of the firm. E.g. with $H = 3$, prices in the $V - Scenario$ are more than 9% lower in 2020 than in the no-shock scenario, implying that the price effect of Corona is largest when firms planning horizon is short. Given a longer planning horizon of 15 years, on the other hand, the Corona shock only decreases price by 2.6% in 2020.

In the long run, however, the difference in aggregate emissions between the no-shock and shock scenarios is minimized if firms apply a very short planning horizon. This finding supports the results of Quemin and Trotignon (2019) who show that in the post-reform ETS shortsightedness leads to a small TNAC and thus low cancellation volumes. For larger planning horizons, additional cancellation volumes caused by the economic shock increase (e.g. with H=15, additional cancellation amounts to 12 Mt CO_2e), so that aggregate emissions are lowest with a longer planning horizon. The waterbed effect decreases substantially ($ERI = 52\%$), implying that with longer planning horizons, larger parts of the the Corona induced emission reduction will also be saved in the long run. This is in line with the findings provided in Bocklet and Hintermayer (2020).

The same holds for price consistency: the longer the planning horizon, the smaller the RPS, indicating that realized prices are relatively closer to the expected prices. While this relationship holds for the pre-reform as well a the post-reform market, the RPS remains lower in the post-reform setting for all shock scenarios and all planning horizons. For $H = 15$ and $\tau = 2020$, for example, the RPS decreases to 4.04 and 0.77 in the pre-reform and post-reform market, respectively.

It can be concluded that the longer the planning horizons of firms, the more effective the reform in decreasing the allowance surplus and increasing price stability in times of crises.

6.1.3. Hedging Requirements

Similar to the parameterization of the planning horizon, there is large uncertainty regarding the precise hedging schedule applied by firms. In order to account for the impact of the hedging schedule, the results of the base case (80% hedging schedule) are compared the results of a 60% hedging schedules, i.e. 60% of the allowance sales are hedged one year ahead, 30% two year ahead and 10% 3 years ahead. Both hedging schedules present the range of likely hedging requirements presented by Eurelectric (2009). As large hedging requirements cause a large TNAC, short-run prices are higher with larger hedging shares. A large TNAC also leads to larger cancellation volumes (e.g. 80% hedging results in more than 4000 Mt CO_2e being canceled, while 60% hedging only leads to an overall cancellation of about 3000 Mt CO_2e). This relationship also holds for additional cancellation caused by the COVID-19 crisis: lower hedging shares lead to lower additional cancellations and larger aggregate emissions in the EU ETS (e.g. for the 60% hedging schedule, $ERI = 17\%$). Consequently, fewer hedging requirements reduce the effectiveness of the MSR reform.

6.2. Shortcomings

The paper at hand relies on simplifying assumption with regards to the size of the economic shock, the calibration of the baseline emissions and the planning horizon and hedging behavior of firms. Thereby, the paper ignores that a crisis might trigger endogenous changes with regard to those parameter assumptions:
On the one hand, a crisis might alter baseline emissions due to endogenous changes in the energy and carbon intensity, as investment decision in the energy sectors might change. Gillingham et al. (2020), for example, point out that the crisis might lead to changing investment decisions in the energy sector, as declining electricity demand could make coal-fired power plants less profitable or financial hardship could lead to declining investments into renewable energies.
On the other hand, the shock might impact the risk aversion of firms, increase the uncertainty in the market and alter the hedging requirements of firms. Tietjen et al. (2019) point out that when the TNAC is large, risk averse firms apply a lower interest rate. Moreover, Salant (2016) finds that uncertainty in the market alters the interest rate applied by firms. Schopp and Neuhoff (2013) further argue that firms adjust their hedging schedules as price expectations change. While the paper at hand considers interest rate and hedging as exogenous variables, an economic shock, such as the COVID-19 pandemic, might impact those variable endogenously.
Future research should therefore be conducted regarding the endogenous interplay of economic shocks, risk aversion and uncertainty.

7. Conclusion

The paper at hand analysis the implication of economic crises on market outcomes in the reformed EU ETS. As the precise market outcomes strongly differ with the size, length and timing of the recession, the Corona crisis serves as an example to quantify short- and

long-run effects of an economic shock on emissions and prices. To do so, multiple crisis' developments are embedded into a discrete-time partial equilibrium model that accurately depicts the current regulatory framework of the EU ETS.
While the numerical results vary between the scenarios and based on the parameter assumptions, the following stylized facts remain valid for all scenarios and parameter constellations:

First, the COVID-19 crisis does not only decrease emissions in the short run but also decreases emissions in the long run within the EU ETS sectors. This remains valid, even if the economic crisis is followed by an economic rebound in the same or larger magnitude as the initial shock. As the recession causes firms to increase their private allowance bank, the Corona crisis increases the MSR intake and triggers additional cancellation from 2023 onwards. The larger the size of the economic rebound, the initial economic shock or the hedging requirements and the longer the planning horizon of a firm, the larger additional cancellation and the lower aggregate emissions in the EU ETS.
Second, while the MSR and the Cancellation Mechanism are able to transfer part of today's emissions' reduction to the future, a significant share of the waterbed effect remains, ranging from 48% to 99%. The actual size of the remaining waterbed effect and the overall effectiveness of the reforms strongly depend on the size of the shock and the underlying parameter assumptions: the longer the planning horizon of a firm, the larger the hedging requirements and/or the stronger the initial reduction in baseline emissions, the smaller aggregate emissions in the EU ETS. On the contrary, if firms are short-sighted, do not hedge and/or the initial shock is rather small, the waterbed effect is almost fully restored, implying that short-run emission reductions will only have little impact on aggregate emissions. Further, the longer the recession, the less effective the MSR mechanism: as firms adjust their decisions, the anticipation effect mitigates the static effect in case of a prolonged crisis, restoring the waterbed effect to a large degree.
Third, if firms do not anticipate an economic rebound after the shock, Corona leads to lower short-run EUA prices than in the no-shock case. The price fall is more pronounced if the initial drop in baseline emission is larger and the planning horizon of a firm is longer. Vice versa, if firms expect an economic rebound in the same or larger size than the initial shock, short-run prices increase compared to the no-shock price level.
Fourth, the ETS reforms increase price consistency during the planning horizon of a firm in times of economic shocks compared to the pre-reform regulatory setting. The longer the planning horizon, the more consistent realized prices with expected prices. This finding

suggests that the reform changes, in particular the MSR and the Cancellation Mechanism, are indeed able to decrease price risk in light of an economic crisis.

Since the the world is currently still in the midst of the pandemic, the paper at hand analyzes the development of the EU ETS market outcomes based on five shock scenarios. Only the future will show how the European economy will develop in response to the COVID-19 crisis. Once the size and the shape of the recession and the potential economic rebound show, further research should be conducted to help policy makers to carefully reevaluate the robustness of the current MSR design with regards to future external shocks.

Appendix A. Lagrangian with Myopia and Hedging Requirements

For the optimization problem $\mathcal{M}(\tau, \mathcal{H})$ (Equation 1) the corresponding Lagrangian is derived by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the respective banking flow constraint and the hedging constraints:

$$\begin{aligned}
&\mathcal{L}(\mathbf{x},\mathbf{e},\mathbf{b},\lambda,\mu_{\mathbf{b}}) = \\
&= \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}\left[\frac{c(t)}{2}(u(t)-e_i(t))^2 + p(t)x_i(t)\right] + \\
&+ \sum_{t=\tau+1}^{\tau+H} \lambda(t)[b(t)-b(t-1)-x(t)+e(t)] - \\
&- \sum_{t=0}^{T} \mu_b(t)[b(t) - \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t}-t)e(\tilde{t})].
\end{aligned} \tag{A.1}$$

Appendix B. Calibration of Kaya Indices

Economic activity index = *industrial production*

Industrial production

2007-2019	Historical data on the Volume Index of Industrial Production of the EU28 from Eurostat (2020).
2019-2100	Productivity index develops from 2019 onwards with 1% growth rate. (Assumption based on IMF (2020).)

Energy intensity index = $\frac{TFEC}{industrial\ production}$

TFEC within EU ETS sectors

1995-2019	Historical data TFEC from electricity, heat, industry & energy-own use and losses in EU28 & Norway from IEA (2020).
2020-2100	Historical share of TFEC of EU ETS sectors on TPEC increases by 0.3% until 2030, by 0.6% between 2030-2040, and 0.4% afterwards. Projections TPEC from EU28 REF16 scenario (E3M-Lab, 2016). Assumption electrification targets from TYNDP (ENTSOG and ENTSO-E, 2020).

Volume Index of Industrial Production -see assumptions stated above.

Energy Intensity Index

1995-2019	Historical Share of TFEC over Volume Index of Industrial Production.
2020-2040	Linear interpolation so that share of TFEC over Volume Index of Industrial Production matches EU Energy efficiency targets for 2020 and 2030 taken from European Commission (2018a).
2041-2100	Asymptotic curvature so that the energy intensity approaches 3250, equivalent to a normalized energy intensity index of 65 (own assumption).

Carbon Intensity Index = $\frac{Emissions}{TFEC}$

TFEC within EU ETS sectors -see assumptions stated above.

Counterfactual emissions in EU ETS Sectors in absent of ETS

1995-2007	Historic data on emissions from oil, coal & gas in electricity, heat, industry & energy own use and losses within EU28 & Norway. TPEC per energy carrier from IEA (2020) and standard emission factors 4.2, 3.1. and 2.4 tonne CO_2e from Quemin and Trotignon (2018).
2008-2019	Reconstructed sectoral emissions based on linear relationship of historic carbon content to historic renewable and nuclear production. TPEC is taken from IEA (2020), renewable production EU28 & Norway is retrieved from OECD (2020), the nuclear production EU 28 from Eurostat (2020).
2020-2100	Projected sectoral emissions constructed based on linear relationship of TPES to projected renewable deployment and nuclear production. Projected TPEC from the EU28 REF2016 scenario (E3M-Lab, 2016) until 2050, TPEC decrease with 1% afterwards (own assumption). Renewable deployment so that EU renewable target 2030 (European Commission, 2018a) will be met linearly and continue to increase with the same rate after 2031. Norway's renewable target will be met based on National Renewable Action Plan, 2012 (Ministry of Petroleum and Energy, 2013). Development of nuclear power production is based on the current nuclear fleet taken from Platts (2016) and updated based on national coal phase out plans, capacity additions from World Nuclear Association (2020) and decommissioning due to end-of-lifetime after 50 years (own assumption).

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