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List of Abbreviations

CLL Carbon Leakage List
CM Cancellation Mechanism
CO_2 carbon dioxide
CO_2e carbon dioxide equivalent
DiD Difference-in-Difference
ERI emission reduction indicator
EUA European Union allowances
EU ETS European Union Emissions Trading System
FDI Foreign Direct Investment
GHG greenhouse gases
IEA International Energy Agency
IMF International Monetary Fund
LRF Linear Reduction Factor
MIP Mixed-Integer Programming
MNE multinational enterprise
MSR Market Stability Reserve
NACE nomenclature of economic activities in the EU
RPS indicator of relative price stability
TFEC total final energy consumption
TNAC Total Number of Allowances in Circulation
TPEC total primary energy consumption
TYNDP Ten Year Network Development Plan
UN United Nations

1. Introduction

Adequately addressing climate change requires an interdisciplinary approach. Natural scientists, engineers, politicians, and economists, among others, must join forces to tackle the biggest challenge of our time. Economists, in particular, are responsible for the design of cost-efficient policy frameworks that ensure effective climate change mitigation and steer multinational cooperation.

Climate change is a common good problem: As no one can be excluded from the climate of our planet, the atmosphere gives a free ride to heavy emitters and thereby weakens the efforts of those that choose to reduce emissions on their end. To address this issue, 196 countries unanimously adopted the Paris Agreement in 2015 and renewed their commitment to combat climate change. However, while the signing parties agree to limit global warming to well below 2°C compared to pre-industrial levels (United Nations, 2015), the agreement lacks the common commitment and reciprocity needed to overcome the problem of free-riding (Cooper et al., 2017).

Instead, each country focuses on voluntary national mitigation policies expressed in their respective "nationally determined contribution". While the strategies to mitigate climate change differ from country to country, many of these national mitigation policies entail a price for carbon. National policy makers hereby aim to internalize the costs of the negative externalities, i.e., the cost of greenhouse gas emissions. Based on economic theory, the internalization of the costs can occur centralized, i.e., through the implementation of a Pigouvian tax (see Pigou (1920)), or decentralized through the allocation of limited property rights (see Coase (1960)). In the former case, a carbon tax is charged to the emitter, with the tax rate having been set based on the marginal damage of emissions. In the latter case, emitters need to surrender certificates that give them the right to emit. These certificates can either be distributed for free or allocated via auctions. By definition, the total supply of certificates restricts the overall emissions in the regulated area. Emission certificates can be traded across regulated entities, leading to a price for carbon.

Without uncertainty and given perfect information, both price and quantity-based instruments result in an equivalent outcome. In reality, however, the true marginal costs of emissions, often referred to as the social cost of carbon, are highly uncertain, with estimates differing widely across models (Nordhaus (2014) and Nordhaus (2017)). Thus, for policy makers, choosing the suitable carbon price to achieve cost-efficient emission reduction, may pose a significant challenge. Therefore, most policy makers favor a quantity-based instrument in the form of an emissions trading system. In this case, the total supply of emission allowances is predetermined based on the desired emissions level, which the market allocates to firms and, over time, ensures that the emission target is met at the least cost.

The largest emissions trading system in place today is the European Union Emissions Trading System (EU ETS). The EU ETS caps emissions originating from around 10,000 plants in the power sector and manufacturing industry in all 27 EU member states, Liechtenstein, Iceland and Norway, covering around 40% of the European emissions (European Commission, 2021b). Since its implementation in the year 2005, the market design of the EU ETS has been substantially amended within four distinct trading periods. The first pilot phase took place between 2005 and 2007, followed by a second trading period beginning in 2008. Since the start of this second phase, firms have been able to bank unused allowances to be used during future trading periods. As a result, lower demand for allowances during the financial crisis in 2009 caused a large build-up of unused allowances at the beginning of Phase III (2013-2020). This led policy makers to amend the market design of the EU ETS substantially in 2015 and 2018, including the introduction of a Market Stability Reserve (MSR), a Cancellation Mechanism (CM), and the tightening of the allowance cap by increasing the Linear Reduction Factor (LRF). In doing so, the allocation of allowances shifted from mostly free distribution in Phases I and II to mostly auctioning in Phases III and IV.

The various reforms of the EU ETS indicate that the market design of an emission trading system is extremely complex. While economic theory suggests that emission trading schemes guarantee the cost-efficient reduction of greenhouse gas emissions, in practice the devil is in the detail. The thesis at hand, therefore, assesses if the EU ETS remains an adequate policy instrument to effectively reduce greenhouse gas emissions despite its complex market design and the changing regulatory framework. In particular, the following questions are to be addressed: Is the EU ETS effective in reducing global greenhouse gas emissions by avoiding carbon leakage to regions outside of its scope? How does the policy design, in particular, the Market Stability Reserve and the Cancellation Mechanism, impact the cost-effectiveness of the system? How do bounded rationality of the market participants and economic developments drive market results?

To answer these questions, the thesis at hand consists of four papers to which the authors contributed equally:

- Chapter 2: Carbon Leakage in the EU ETS - Evidence from the Empirical Literature and Implications for Phase IV.
- Chapter 3: The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking. Joint work with Martin Hintermayer, Lukas Schmidt, and Theresa Wildgrube, *EWI Working Paper 19/04* and published in *Energy Economics*. See Bocklet et al. (2019)
- Chapter 4: How Does the EU ETS Reform Impact Allowance prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule. Joint work

with Martin Hintermayer, *EWI Working Paper 20/01.* See Bocklet and Hintermayer (2020)

- Chapter 5: The Reformed EU ETS in Times of Economic Crises: the Case of the COVID-19 Pandemic, *EWI Working Paper 20/10.* See Bocklet (2020)

The remainder of this introduction is structured as follows: Section 1.1 provides an overview on the content of the four essays, including the respective research questions, methodological approaches, and key findings. Section 1.2 discusses the methodological differences among the papers, potential shortcomings, and areas of further research.

1.1. Outline

The meta study provided in Chapter 2 introduces the reader to the EU ETS and discusses if the market design reduces global emissions effectively by limiting carbon leakage. Carbon leakage hereby refers to the phenomenon that, in response to environmental regulations such as an ETS, emissions shift from a regulated region to an unregulated region, causing the same or even higher emissions than before the introduction of the policy. To shed light on this issue, the empirical literature on carbon leakage in the EU ETS is systematically reviewed and categorized. Special attention is paid to the underlying regulatory framework assessed by these studies and the market developments that may have impacted the empirical results. The chapter reveals that the empirical literature finds almost no evidence of carbon leakage in the past. This is likely due to market developments (e.g., such as low allowance prices) but also due to the policy design, which included free allocation to vulnerable sectors. Yet, studies that cover data from Phase III and/or focus on trade-intensive sectors show increasing foreign direct investments. Therefore, common drivers of carbon leakage and the implications for Phase IV are assessed, taking into account the restrictive carbon leakage criterion adopted during this trading period. The discussion reveals that, on the one hand, the carbon leakage risk may increase during Phase IV as EUA prices are expected to rise and fairly mobile sectors no longer qualify for free allowance allocation. On the other hand, most large emitters will continue to receive free allowances in the future, even if low to moderate trade intensity suggests that the risk of carbon leakage is low. This implies that the carbon leakage criterion should be reassessed if policy makers aim to maximize the auction share.

Chapter 3 shifts the focus to the third trading period, during which the regulatory rules of the EU ETS were fundamentally altered. More specifically, the impact of the increase of the LRF, the implementation of the MSR, and the introduction of the CM on market outcomes is assessed. In doing so, a discrete-time model of the inter-temporal allowance market is developed in which prices rise with the Hotelling rule as long as the aggregated allowance bank is non-empty.

The respective reform steps are individually embedded into the model. This allows the single effects of the amendments on market outcomes to be decomposed and the cost effectiveness of the different reforms to be evaluated. The results show that the MSR shifts allowances to the future but preserves allowances over time. The CM does not impact the emission and price paths in the short run but increases allowance prices in the long run through a one-time cancellation of around 2 billion allowances. The new LRF reduces the overall allowance cap by 9 billion allowances and is thus the main price driver among the three amendments. The analysis further reveals that, whereas the MSR on its own decreases the cost effectiveness of the EU ETS, the introduction of the CM increased the cost effectiveness. Yet, an equivalent exogenous shortening of the allowance supply would be superior to the CM as cost effectiveness could be increased even further. While the parameterization drives the numerical solutions, an extensive sensitivity analysis ensures the robustness of the key results.

The Hotelling model set up in Chapter 3 assumes perfect markets and fully rational firms. In reality, however, firms are likely to not be perfectly rational but rather prone to bounded rationality. Therefore, it is not surprising that the theoretical results depicted in Chapter 3 are not capable of replicating the real historic market outcomes between 2013 and 2019 when EU allowance (EUA) prices quadrupled. Chapter 4 therefore amends the model by considering two forms of bounded rationality. Given that firms are myopic and bound to exogenous hedging requirements, the price spike can be explained by the amended Hotelling model. While neither form of bounded rationality is able to explain the market outcomes on its own, the model is able to replicate the development of real allowance prices and the private bank, once they are jointly considered. Moreover, this chapter reveals that the aforementioned reforms mitigate the market distortion caused by myopia. Hedging requirements have little impact on the pre-reform market but are the key price driver after the reforms. Large hedging requirements may even lead to a physical allowance shortage in the market.

Chapter 5 uses the amended Hotelling model developed in the previous chapter to assess if the MSR and the CM increase the market's resilience against economic shocks. The COVID-19 pandemic hereby serves as an example of an unforeseen contraction of the European economy. Contrary to the model parameterization used in the two previous chapters, Chapter 5 constructs baseline emissions before and after the economic shock with the help of the Kaya identity. The model results indicate that 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. Furthermore, the MSR and the CM increase the robustness of the market towards economic shocks by stabilizing prices. The absolute emission reduction and the relative price stability when faced with an economic crisis yet strongly depend on the shape and size of the shock as well as the planning horizon of firms in the market.

1.2. Methodology, Shortcomings and Future Research

All chapters of this thesis evaluate the market design of the EU ETS under various reform stages. Chapter 2 conveys a meta study of empirical literature that assesses carbon leakage in the EU ETS in Phase II and beyond. While there is no claim of completeness, the meta study focuses on 14 empirical, peer-reviewed publications that are most relevant to the research question. In a first step, the empirical literature is mapped, key findings summarized and methodological caveats discussed. In a second step, the drivers of carbon leakage are categorized. In a last step, implications for Phase IV are discussed. The meta study reveals that there is a lack of empirical literature on carbon leakage in Phase III. As the regulatory framework changed significantly in this trading period and prices significantly rose, more empirical research is needed to generate findings for carbon leakage in later phases of the EU ETS.

The remaining chapters all use a partial equilibrium model of the EU ETS that builds on the seminal work of Hotelling (Hotelling, 1931). A number of homogeneous firms N minimize their abatement costs and the cost for allowance purchasing. The Karush-Kuhn-Tucker (KKT) conditions derived from the cost minimization problem provide a feasibility problem for the market equilibrium. The discrete regulatory rules are included and the problem is set up as a Mixed-Integer Programming problem (MIP), implemented in GAMS. Non-linearities in the regulatory framework are approximated via the Big M Method. In Chapter 3, firms are assumed to have perfect foresight and are fully rational. In the following chapters these assumptions are relaxed by explicitly allowing for myopic players and firms subjected to hedging requirements. Other forms of bounded rationality and further market imperfections are not captured by the models. In particular, the role of uncertainty and technological learning are promising research areas for future work.

The thesis presents numerical models that accurately depict the regulatory framework of the EU ETS. Developments in other markets are assumed to be exogenous. While this allows for closed-form solutions and keeps the models computationally tractable, this simplification leads to a deviation of the model results from real-world developments. Of particular importance are the assumptions on the interest rates, baseline emissions and abatement costs curves, which are all driven by developments in other markets. As shown by the sensitivity analysis in Chapter 3, higher interest rates lead to lower short-run prices and vice versa. Therefore, future models should link the EU ETS to financial markets to capture the effect of fluctuating interest rates over time. Another assumption that drives the numerical results is the assumption on the baseline emissions. While Chapters 3 and 4 assume constant baseline emissions over time, the baseline emissions in Chapter 5 are constructed using the Kaya identity to capture market developments in absent of an emission trading system. Future work should build on this approach to model real-world economic developments more closely. Furthermore, the models used throughout this thesis assume quadratic abatement costs, resulting in linear marginal abatement cost curves. Yet, the work of Hintermayer et al. (2020) reveals that marginal abatement cost curves in the power market tend to be convex. As the shape of the abatement cost curves drives the banking of allowances in the EU ETS, future research should aim to incorporate more realistic cost curves into their models.

Comprehensive descriptions of the methodological approaches as well as further research avenues are provided within the respective chapters.

Of course, the future of the EU ETS remains unknown as the design and regulation continue to evolve. Just recently, the European Commission proposed further amendments to the EU ET in light of the 'Fit for 55' legislative package (see European Commission (2021a)). In addition to the inclusion of the maritime sector into the EU ETS, the Commission proposed to increase the MSR's intake rate as well as the LRF in Phase IV. The models developed throughout this thesis are able to assess the impact of such regulatory changes on market outcomes. Further research should thus build on the work provided in this thesis to evaluate if proposed changes in the policy framework of the EU ETS are capable to meet the overall EU climate goals.

2. Carbon Leakage in the EU ETS - Evidence from the Empirical Literature and Implications for Phase IV

2.1. Introduction

In December 2019, the European Commission published the "European Green Deal" (European Commission, 2019a) – a policy initiative calling for increased ambitions in the fight against climate change. While the document affirms the EU ETS to be the fundamental pillar of European climate change policy, the European Green Deal also emphasizes the risk of carbon leakage because "many international partners do not share the same ambition as the EU" (*ibid, p.5*).

The carbon price imposed by the ETS inflicts a cost on regulated firms that does not occur to firms outside of the regional scope of the EU ETS. This potentially increases emissions outside of the EU in response to the domestic ETS regulation - a phenomenon coined as carbon leakage.[1]

To prevent carbon leakage and to ensure the economic viability of EU firms, policy makers can either impose a tax on firms in non-regulated regions or support domestic firms that are especially vulnerable to carbon leakage. While the European Green Deal proposes a carbon border adjustment mechanism, the EU ETS currently relies on the latter option by allocating free EU allowances to vulnerable firms.

In 2019, the carbon leakage criterion that determines which EU ETS sectors qualify for free allowances was reassessed. This led to a substantial reduction of firms on the carbon leakage list (CLL) from 2021 onwards.

The reduction of the CLL gives rise to the question of whether carbon leakage infringed the effectiveness of EU ETS policy in previous trading periods, and if these findings still hold in light of the new carbon leakage criterion for Phase IV.

To shed light on this issue, the paper at hand provides a meta study that focuses on 14 empirical, peer-reviewed publications that aim to assess carbon leakage in the EU ETS through quantitative modeling approaches. In a first step, the empirical literature is reviewed and the results are depicted. Furthermore, differences in the methodological frameworks of the studies are analyzed and it is discussed if the quantitative results can be used to qualitatively assess

[1] The potential shifting from inner-European emissions from ETS to non-ETS sectors is beyond the scope of this chapter.

carbon leakage in the EU ETS. In a second step, the drivers of carbon leakage found by the literature are categorized and it is assessed if the EU carbon leakage regulation adequately addresses those determinants. In a third step, implications for Phase IV are discussed in light of the new carbon leakage regulation. The study at hand hence differs in scope and focus from the literature reviews provided by Joltreau and Sommerfeld (2019) and Verde (2020). Both studies review the literature with a special focus of the impact of the EU ETS on the competitiveness of regulated firms. Verde (2020) hereby reviews 35 peer and non-peer reviewed studies with a close focus on differences in the modeling approaches used. Joltreau and Sommerfeld (2019) provide systematic reasoning for why there have been no negative effects found in Phase I and II. In contrast, the paper at hand pays special attention to the underlying carbon leakage regulation and evaluates potential changes for Phase IV.

Carbon leakage mainly occurs due to the following two direct effects[2]:

Terms-of-trade effect: due to a comparative disadvantage of domestic firms caused by the carbon price, market shares of firms regulated by the EU ETS decrease. Given the change in terms-of-trade, unregulated firms outside of the EU will increase the production of the respective product, potentially increasing emissions outside of the EU (Dröge et al., 2009).

Relocation effect: due to the carbon price established by the ETS, the production costs of a firm increase, likely decreasing the firm's profits. Firms thus shift their domestic (industrial) production capacities to countries with no or fewer environmental policies[3] (Dröge et al., 2009).

From the literature reviewed it can be concluded that no large scale carbon leakage took place during EU ETS Phase I to III. Some studies that focus on the long-run competitiveness of European firms yet find that foreign direct investments increased to a small extent. This might be an early warning indicator that carbon leakage could occur in the future.

Yet, the results from these studies need to be treated with caution, as the response variables used in these empirical models do not capture the phenomenon of carbon leakage to the full extent. Furthermore, low EUA prices and the carbon leakage regulation in place, which includes free allowance allocation, were likely successful in preventing carbon leakage in the past.

While the carbon leakage list for Phase IV is substantially reduced, mostly small emitters were deleted from the list. Many emission-intensive sectors are

[2]While this chapter focuses on the direct effects, it should be noted that carbon leakage also occurs through indirect effects, such as a decreasing global fuel price or rising domestic electricity prices. In contrast, technology and policy diffusion likely induce positive spillover effects that counteract some of the carbon leakage. Di Maria and Van der Werf (2008) coin this effect as induced-technology-effect.

[3]Such a relocation of production capacities to a region with less stringent environmental policies is often referred to as the "pollution haven hypothesis" (Borghesi et al., 2020).

still covered on the CLL, even if they are rather immobile and not trade-intensive, implying that the carbon leakage risk for those sectors is rather low. As some studies suggest that free allowance allocation dampers investments into low-carbon technologies, a further reduction of the list could increase the dynamic efficiency of the market. However, the meta study reveals that the share of free allowance allocation, EUA prices, and the capital intensity of sectors drive the carbon leakage decision of the regulated entities. In light of the higher EUA auction share for Phase IV and the recent upward trend in EUA prices, carbon leakage rates might potentially increase in Phase IV.

The remainder of this chapter is structured as follows:

Section 2.2 gives an overview of the EU ETS and the development of the carbon leakage criterion. In Section 2.3 the empirical literature is mapped, results explained and methodological differences discussed. In Section 2.4 key determinants of carbon leakage are systematically reviewed and the carbon leakage regulation assessed. Section 2.5 shows potential implications for Phase IV. Section 2.6 concludes.

2.2. EU ETS Regulation and the Carbon Leakage List

In 2005, the EU ETS was launched as the central pillar of the European climate change policy. The EU ETS is designed to internalize the cost of greenhouse gas emissions in a cost-efficient way. The cap-and-trade system hereby covers emissions from more than 10,000 installations of the power and manufacturing sector and inner-European aviation. Since the beginning of the EU ETS, policy makers acknowledged that carbon leakage would reduce the effectiveness of the EU ETS in reducing global greenhouse gas emissions. The carbon leakage regulation of the EU ETS thus aims to prevent carbon leakage and to ensure the effectiveness of the unilateral climate change policy (see Section 2.2.1). Based on this regulation, the CLL, a registry of sectors that are prone to carbon leakage, is established (see Section 2.2.2).

2.2.1. Development of EU ETS Carbon Leakage Regulation

Since its introduction, the regulatory framework of the EU ETS has been revisited and substantially amended over the course of four distinct trading periods:

The first trading period, referred to as Phase I, lasted from 2005 to 2007. During this time, the EU ETS covered emissions from power generations and energy-intensive industries, and almost all EUA were distributed free of charge in order to avoid carbon leakage. In absence of reliable data on historic emissions, the allowance cap for the first phase was based on estimates. As allowance supply exceeded allowance demand and firms were not allowed to transfer unused allowances to the next trading periods, the EUA price fell to zero at the end of Phase I. While the first phase was considered a "trial and error phase", it succeeded in developing the infrastructure for emissions trading across the EU and establishing a price for carbon (European Commission, 2021b).

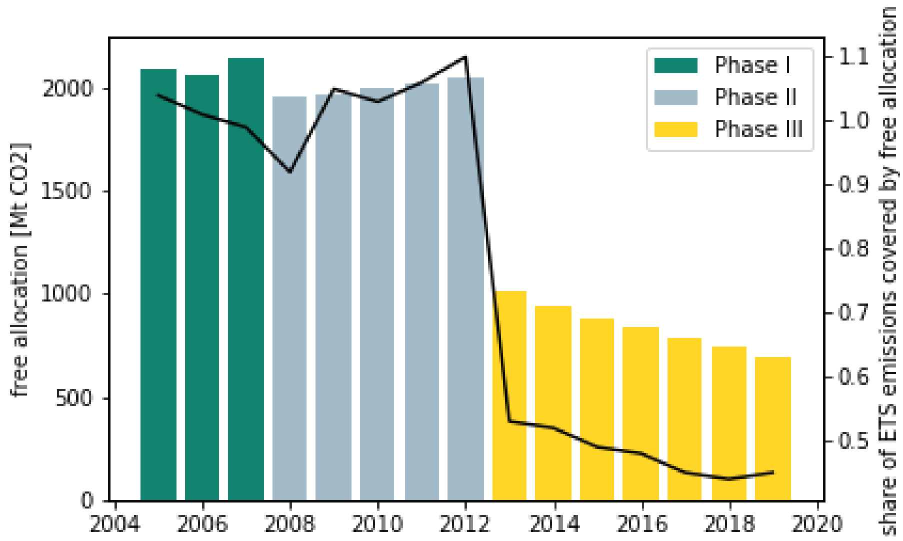

Figure 2.1.: Annual number of free allowances and share of emissions covered by free allowance allocation in Phase I-III

Own representation based on data provided by Sandbag (2021)

In Phase II (2008-2012), the EU ETS was expanded in scope, as Iceland, Liechtenstein, and Norway joined the system. The share of allowances allocated for free fell from 95% in Phase I, to 90% in Phase II. Free allowances were distributed based on a grandfathering mechanism, i.e., firms received EUA based on their historic emissions. Further, the allowance supply was lowered, the penalty for non-compliance increased and allowances could be transferred from one trading period to another (European Commission, 2021b). During these first two trading periods, member states determined the number of allowances to be allocated for free on the national level.

This changed with the third trading phase (2013-2020), when the free allocation of EUA was harmonized across all member states. The allocation of free allowances shifted from a grandfathering mechanism to the use of benchmarking, rewarding installations with efficient production.[4]

EU ETS Phase IV commenced in 2021 and will last until 2030. During this phase, the European Commission aims to reduce emissions more strongly, while avoiding large-scale carbon leakage. As the declared goal is to establish a "better-

[4] A detailed description of the benchmarking mechanism can be found in Martin et al. (2014).

targeted carbon leakage framework" (European Commission, 2021b), free allocation of allowances is restricted to sectors with the highest risk of carbon leakage. To meet this goal, the CLL for Phase IV became more restrictive.

While the amount of freely allocated allowances thus decreased over time (see Figure 2.1), sectors listed on the CLL are still entitled to 100% free allocation.

2.2.2. The Carbon Leakage List

Based on regular assessments, the European Commission identifies subsectors on the four-digit NACE code level[5] that are particularly vulnerable to carbon leakage. The first carbon leakage assessment was applied from 2013 to 2014 (European Commission, 2009), the second one from 2015 to 2020 (European Commission, 2014b) and the latest assessment will be valid throughout Phase IV (European Commission, 2019b).

During the first two assessments (see European Commission 2009 & 2014), a sector received free allowances and was hence exempt from auctioning if one of the three following criteria was met[6]:

Emission criterion: the direct or indirect costs induced by the ETS[7] are more than 30% of the gross value added of the respective sector.

Trade criterion: the trade indicator for a sector, calculated as imports plus exports over domestic production, is at least 30%.

Combined Trade and Emission criterion: the trade indicator of the sector exceeds 10% while the carbon intensity indicator is larger than 5%.

Sectors that meet one of the three criteria are included on the CLL.

As free allowances can be sold on secondary markets, economic theory suggests that due to these opportunity costs, the allocation mechanism should not impact a firm's abatement decision. Empirical evidence and interviews among decision makers yet reveal that firms that receive allowances for free are less likely to invest in product innovation (Martin et al. (2011) and Cooper and Dröge (2011)). Additionally, free allocation implies lower revenues for states and comes thus with opportunity costs (Martin et al., 2014).

Therefore, many have argued that the indicators had been inappropriately set and/or their thresholds had been too low and thus criticized the large number of sectors included on the carbon leakage list (see e.g. Cooper and Dröge (2011)).

[5]The NACE code is the European industry-standard classification system that groups organizations based on their business activities. Four hierarchical levels are used, ranging from 21 one-digit economic areas to 629 four-digit subsectors.

[6]In addition to these quantitative criteria, policy makers could also apply a qualitative assessment on the impact of the ETS on production costs, investments and profit margins.

[7]For the calculation of the direct and indirect costs, an average EUA price of 30 EUR is assumed.

Policy makers thus decided to adjust the carbon leakage criteria for Phase IV. The level of carbon leakage exposure of sectors is now assessed using a carbon leakage indicator instead of the three criteria explained above, so that

$$indicator = emission\ intensity * trade\ intensity, \tag{2.1}$$

whereas

$$emission\ intensity = \frac{direct\ emissions + indirect\ emissions}{gross\ value\ added}, \tag{2.2}$$

and

$$trade\ intensity = \frac{exports + imports}{turnover + imports}. \tag{2.3}$$

The equations show that the established factors that drive carbon leakage, such as direct and indirect emissions, gross value added and trade indicators, have not changed. New is that only the emissions and not the costs of emissions are taken into account. Further, only the product of trade and emission intensity is considered. Thus, sectors that are e.g. highly emission-intensive but have a very low trade intensity, are no longer captured by the new indicator. Also, the threshold is tightened: If the carbon leakage indicator exceeds a threshold of 0.2, an industry is considered to be highly exposed and will receive EUA equivalent to 100% of the respective benchmark value for free.[8] Installations within sectors that are determined to be "less exposed to carbon leakage" and thus no longer included on the CLL, will receive 30% of the respective allowances for free until 2026. Afterward, free allocation will gradually phase out until 2030 (European Commission, 2021b).

The application of the new carbon leakage criterion led to a substantial reduction of industries on the latest CLL so that only 50 out of 147 four-digit NACE sectors previously included on the list, also qualify for free allowance allocation in Phase IV. See Table A.1 for an overview of all sectors on the list.

2.3. Overview of the Empirical Literature

The following section provides an overview of the existing empirical literature on carbon leakage in the EU ETS. First, the criteria for the literature selection

[8] A sector can still be included on the CLL even if it does not meet the quantitative threshold but if a qualitative assessment, based on abatement potential, market characteristics, and profit margins, reveals that the sector is prone to carbon leakage (European Commission, 2019b).

are described (Section 2.3.1). Then, the key findings of the literature are shown (Section 2.3.2) and the methodological approaches applied are critically assessed (Section 2.3.3).

2.3.1. Selection of Literature

There is a large strand of literature on carbon leakage. In order to answer the research question, the vast literature was narrowed down to 14 studies which were selected based on the following criteria:

First, among all publications on carbon leakage, this paper only analyzes articles published in peer-reviewed journals.

Second, only papers that focus explicitly on the EU ETS are used, setting aside findings from a large strand of literature on negative externalities of other environmental policies and from studies on carbon pricing in other regions.

Third, while there is a vast literature strand on the theoretical threat of carbon leakage in the EU ETS, this paper focuses exclusively on the findings from empirical studies.

Fourth, as the first phase of the EU ETS was considered a pilot phase, this paper only assesses literature that covers at least one year from the second phase of the ETS.

Fifth, this paper understands carbon leakage as an increase in emissions outside of the regional scope of the EU ETS due to a change in the profitability of the regulated entity. Changes in trade relations, economic performance, and investment decisions of the regulated entity are used as proxies for carbon leakage. Studies that focus on the distributional effects between ETS sectors and non-ETS sectors within the EU or that evaluate shareholder expectations based on stock returns, are not considered.

An overview of the literature that fulfills these selection criteria, including approaches used, geographical and temporal scope, and key results of the respective studies, is provided in Table 2.1.

The focused scope of this literature review and the selection of studies that include data from the second and third trading period, enable us to focus in detail on the results and methodological differences and to determine common factors that drive carbon leakage. This allows us to also discuss potential implications for Phase IV.

Table 2.1.: Overview of empirical studies on carbon leakage in EU ETS Phases I, II and III

Article	Response Variables	Method	Temporal Scope	Countries	Sectors	Level	CL?
Chan et al. (2013)	material costs, employment, revenue (*economic performance*)	DiD	2005-2009	10 EU countries	cement, iron, steel, power	firm	no evidence
Lundgren et al. (2015)	total factor productivity (*economic performance*)	panel regression	2005-2008	Sweden	pulp and paper	firm	no evidence
Borghesi et al. (2015)	energy use per output unit, energy use per CO_2 emission (*effectiveness*)	panel regression	2005-2008	Italy	manufacturing	firm	no evidence
Branger et al. (2016)	net imports (*trade-effect*)	time series regression	2005-2012	EU27	cement, steel	industry	no evidence
Jaraite-Kažukauske and Di Maria (2016)	CO_2 emissions, CO_2 intensity, investments, profitability (*effectiveness & economic performance*)	DiD	2005-2010	Lithuania	multiple	firms	no evidence
Boutabba and Lardic (2017)	net imports (*trade-effect*)	time series	2005-2015	multiple	cement, steel	industry	some evidence
Marin et al. (2018)	productivity, wages, turnover, value added etc. (*economic performance*)	DiD	2005-2012	20 EU countries	multiple	firm	no evidence
Moore et al. (2019)	fixed asset base *relocation-effect*	DiD	2005-2012	multiple	multiple	firm	no evidence
Koch and Basse Mama (2019)	FDI *relocation-effect*	DiD	2005-2013	Germany	manufacturing	multiple	some evidence
Löschel et al. (2019)	value of production (*economic performance*)	DiD	2005-2012	Germany	manufacturing	firm	no evidence

Makridou et al. (2019)	profitability (*economic performance*)	panel data	2006-2014	19 EU countries	multiple	firm	some evidence
Borghesi et al. (2020)	FDI *relocation-effect*	DiD	2005-2010	Italy	manufacturing	firm	some evidence
Carratù et al. (2020)	profit *economic performance*	DiD	2009-2016	multiple	multiple	firm	no evidence
Klemetsen et al. (2020)	value added, labor productivity *economic performance*	DiD	2005-2013	Norway	manufacturing	plants	no evidence

2.3.2. Key Results

As mentioned in the previous section, this chapter focuses on articles that evaluate the change in trade relations, investment decisions in unregulated regions, the effectiveness of EU ETS policy, and changes in the economic performance of firms. Irrespective of the different carbon leakage indicators assessed, the majority of studies do not find evidence of carbon leakage:

The results shown in Chan et al. (2013), Lundgren et al. (2015) and Carratù et al. (2020) indicate that the EU ETS neither incentivized investments into low carbon technology nor decreased the economic performance of firms, suggesting that the EU ETS did not significantly affect the decision making of regulated firms.

Borghesi et al. (2015), Jaraite-Kažukauske and Di Maria (2016), Marin et al. (2018), Löschel et al. (2019), and Klemetsen et al. (2020) even find a positive effect of the ETS on a firm's performance:

Löschel et al. (2019) estimate that the EU ETS increased the value of production of German manufacturing firms. The effect is most pronounced for the early years of Phase I and for a subset of firms in the German pulp and paper industry. Klemetsen et al. (2020) on the other hand find that the economic performance of Norwegian manufacturing plants - measured in value added and labor productivity- increased especially in Phase II, by 24% and 26%, respectively. As the Norwegian ETS was only formally linked to the EU ETS in 2008, both studies yet mutually imply that the EU ETS especially impacted a firm's performance during its inauguration phase. Higher investments and lower CO_2 intensities are found by Jaraite-Kažukauske and Di Maria (2016) for Lithuanian firms in Phase II, suggesting that the ETS was effective in steering investments into low-carbon technology. In line with this suggestion, Borghesi et al. (2015) show that the energy efficiency and the CO_2 abatement of Italian manufacturing firms increased between 2005 and 2008. Marin et al. (2018) evaluate the economic performance of regulated firms from 19 EU countries and the UK. The results show that the findings from the sectoral- and country-specific studies mentioned above can be confirmed on a more general level when cross-country and cross-sectoral effects are evaluated. Besides higher labor productivity, the authors also find a positive effect of the EU ETS on markup, investment intensity, and turnover.

The studies mentioned above thus do not find a negative impact of the ETS on the profitability of regulated firms or even imply that the EU ETS increased domestic investments and improved the economic performance of regulated firms. Hence, no indication for carbon leakage during Phase I-III is found. This could imply that the EU carbon leakage regulation was effective in the respective time frame.

A similar conclusion can be drawn from studies that evaluate the short- or long-term international competitiveness of regulated firms:

Branger et al. (2016) evaluate net imports in the cement and steel industry of the EU27 during 2005 and 2012 and find no evidence that the international competitiveness of the respective sectors decreased in the time frame analyzed. Moore et al. (2019) determine the asset base of more than 7000 firms regulated by the EU ETS. Similarly, they find no evidence of carbon leakage, even for global MNEs that have a presence in countries outside of the EU. This implies that even firms with low relocation costs did not move their capital to countries with supposedly lower environmental regulation.

Four of the studies reviewed find at least some evidence of carbon leakage, either by finding negative effects of the EU ETS on the performance of regulated firms or by providing evidence that firms are planning to relocate in the future:

Makridou et al. (2019) evaluate firms from eight different sectors located in 18 EU countries and the UK from 2006-2014 and find that the total number of allowances that need to be auctioned to cover a firm's emissions, decreases the profitability of the firm. As the auction share increases over time, the profitability of a firm declines, and the risk of carbon leakage increases.

Borghesi et al. (2020) find some evidence of carbon leakage when evaluating the FDI of 283 Italian manufacturing firms between 2005 and 2010. While the ETS had only a weak effect on the number of subsidiaries set up outside of the EU, the ETS increased sales rates of existing foreign subsidiaries, especially in non-OECD countries. This implies that internal production moved to countries with less stringent environmental policies. The effect is most pronounced for trade-intensive sectors.

Similar results are found for German MNEs between 2005-2013, especially in the manufacturing sector: There is a small positive effect of the ETS on FDI. While the effect becomes more pronounced for MNEs that are less capital intensive, the behavior of MNEs from sectors on the carbon leakage list is not statistically different than the behavior of other regulated MNEs (Koch and Basse Mama, 2019).

Boutabba and Lardic (2017) find some evidence of carbon leakage by evaluating net imports of the EU cement and steel industries. While net imports increased, the absolute size of the effect is small and more pronounced for the steel than for the cement industry.

2.3.3. Comparison of Research Approaches, Critical Assessment and Limitations

While the results depicted above provide mixed evidence on historic carbon leakage in the EU ETS, the majority of the studies find that the ETS did neither negatively affect firms' economic performances nor decreased their international competitiveness. While carbon leakage is defined as an increase in emissions abroad caused by the domestic EU ETS, none of the studies is able to measure this shift in emissions. Instead, all of the studies rely on proxies. Yet, it is debatable to what extent the alternative response variables are suitable proxies for carbon leakage.

Even if the response variables are suitable choices in measuring carbon leakage, missing evidence could imply that the carbon leakage regulation was effective. Thus the results need to be treated with caution as the studies differ with regards to the methodology and the resolution level of the data applied and are likely not representative due to limitations in their geographical and temporal scope.

Hence, in the following the differences among the studies and potential limitations are evaluated. First, differences in the response variables and their suitability to capture carbon leakage are assessed. Second, I compare the methodologies applied within the different articles. Third, the granularity of the data with regards to the entity level, the geographical scope, and the temporal resolution are discussed.

Response Variables

The declared goal of the reviewed studies is, to explore if EU ETS regulation led to carbon leakage by increasing emissions outside of the regional scope of the EU ETS. To answer this question, the studies rely on quantitative assessments. As it is not possible to measure emissions in absence of the ETS, they use proxies, such as the economic performance of firms, the effectiveness of ETS regulation, and trade and relocation effects, as response variables.

However, it is questionable if these quantitative measurements are capable of capturing the effect of the EU ETS on carbon leakage rates.

Two papers (Borghesi et al. (2015) and Jaraite-Kažukauske and Di Maria (2016)), evaluate the effectiveness of the ETS regulation by determining its impact on CO_2 emissions and the energy efficiency of regulated industries. If the EU ETS does not steer investments into energy efficiency and does not decrease emissions in regulated sectors, ETS policy is considered ineffective and thus does not impact the economic performance of the regulated firm. A reduction in the economic performance of a firm is understood as an early warning indicator that the international competitiveness of the firm decreases which could trigger a change in the terms-of-trade or lead to relocation in the future. Lundgren et al. (2015) and Marin et al. (2018), among others, determine the impact of the EU ETS on the economic performance of a firm. If the production value or the profits of firms decrease due to carbon pricing, they might close down their regulated facilities and/or relocate their production to countries with lower CO_2 prices.

An ineffective policy and/or no impact on the economic performance of a firm is thus considered an indirect indicator that carbon leakage is low. Yet, this causality is potentially flawed: First, evidence that the ETS does not steer investments into energy efficiency does not necessarily imply that no carbon leakage took place. Contrarily, missing investments at home could also imply that larger investments are planned in unregulated regions. Second, if firms expect tighter regulation in the future, carbon leakage likely occurs even if the economic performance today is not negatively impacted by the current EU ETS regulation.

Another strand of literature focuses directly on the change in trade relations and higher investments in unregulated regions, which reflect the terms-of-trade effect and the relocation-effect, respectively, explained in Section 2.1. Five of the studies reviewed assess those direct effects of carbon leakage. In the short-run, decreasing international competitiveness can be measured through larger net imports (see Branger et al. (2016) and Boutabba and Lardic (2017)). In the medium to long run, multinational enterprises (MNEs) can choose to relocate production from their regulated installation to an unregulated installation abroad (see Moore et al. (2019)) or by investing in new plants outside of the EU (relocation effect). The later can be measured as an increase in Foreign Direct Investments (FDI) (see e.g. Koch and Basse Mama (2019) and Borghesi et al. (2020)). An increase in net imports, a reduction of the EU asset base, and an increase in FDI, therefore, serve as proxies in the literature to determine short, medium, and long-run carbon leakage, respectively. However, a change in investments or trade relations does not necessarily mean, that emissions shifted abroad due to the introduction of the EU ETS. Instead, other economic drivers such as changes in labor prices, resource availability, currency exchanges rates, or firm-specific internationalization strategies, drive the quantitative results. Yet, none of the models used is able to differentiate between changes in response to the EU ETS and other economic drivers.

While studies focusing on trade relations and higher investments are likely more suitable to measure carbon leakage than studies relying on the indirect indicators mentioned above, the quantitative assessments are yet not fully able to answer the qualitative question on carbon leakage.

Methodological Approaches

While all studies considered apply some sort of econometric modeling, they differ in the precise approaches used: nine studies compose a Diffence-in-Difference (DiD) analysis, three use other forms of panel data regressions and two provide estimations using time-series regression methods.

Most DiD studies reviewed use a panel data set of firms in EU ETS member states that entails firm-, industry- and policy-specific characteristics over multiple years. The firms that are regulated by the ETS hereby serve as the treatment group which is matched, e.g. via nearest-neighbor matching, to a control group of firms that are not subject to the ETS regulation. The difference in the response variables of the respective match is then attributed to the regulation. Identifying a suitable control group that is common to the treatment group in all other characteristics but the treatment is thus critical for a DiD analysis.

While the majority of DiD studies match treatment and control groups on the firm level, Klemetsen et al. (2020) match regulated manufacturing plants to unregulated manufacturing plants. However, in reality, installations that have to comply with the EU ETS are not chosen at random but based on their plant characteristics. Thus, regulated plants are likely systematically different than unregulated installations. Matching at the individual installation level might thus ignore confounding variables, challenging the validity of the respective results.

The remaining DiD studies circumvent this problem by aggregating installations to the firm level, allowing matching between regulated and unregulated firms with the same trends and characteristics. Löschel et al. (2019) determine matches on the two-digit NACE level for different manufacturing sectors. They develop an efficient production frontier that expresses the maximum amount of output that can be produced with a given set of inputs with a fixed technology. The distance of a manufacturing firm to the respective frontier serves as an indicator of a firm's economic performance. However, ETS regulation likely impacted firm-specific characteristics during the treatment phase. Other papers thus apply a bias-adjusted matching which accounts for systematic time-invariant differences in the response variable. The control group chosen is thereby matched to the treatment firm based on pre-policy characteristics. Chan et al. (2013), for example, match regulated and unregulated firms in the respective sectors based on their development in unit material costs, revenue and employment prior to the introduction of the ETS. Correspondingly, Koch and Basse Mama (2019) and Moore et al. (2019) match regulated MNEs to a control group of unregulated MNEs based on similar firm attributes in the year 2004. Contrary to the papers described above, Koch and Basse Mama (2019) hereby match firms based on three-digit NACE classifications, instead of the two-digit sectoral level.

Lundgren et al. (2015), Borghesi et al. (2015) and Makridou et al. (2019) use other forms of panel regressions that do not require the computation of a counterfactual as needed for the DiD estimates. Lundgren et al. (2015) estimate the impact of the ETS on the total factor productivity, technological development, and technical efficiency change with a generalized method of moment estimator in a dynamic panel data approach. This technique allows the use of lagged variables and hence captures the dynamic nature in firms' decision making. Borghesi et al. (2015), on the other hand, estimate the impact of multiple environmental policies in Italy on energy reduction per unit of output and CO_2 reduction in a probit model. The effect of the EU ETS on the response variables is hereby captured by a dummy variable. Makridou et al. (2019) use a hierarchical linear multilevel approach which distinguishes between variability over time, firm-level variability, and the variability across countries and sectors. They hereby estimate the impact of EUA prices and the share of freely allocated EUA on the financial performance of regulated firms.

While all papers mentioned above include multiple plants or firms, Branger et al. (2016) and Boutabba and Lardic (2017) use times series data to estimate the effect of ETS policy on industrial sectors. Branger et al. (2016) determine carbon leakage in the cement and steel industries using the increase of net imports as a proxy for short-term carbon leakage. The model specifies these net imports through carbon prices and demand indicators for the respective industry. ARIMA regressions with Prais-Winsten estimations are used to avoid serial correlation in the model. The model is extended by Boutabba and Lardic (2017) who add the currency exchange rate and overall energy prices as explanatory variables. They further account for structural breaks caused by the regulatory changes of the different ETS phases within a rolling-cointegration approach.

While the papers differ in regard to the methodology used, it can be concluded, that there is no obvious pattern that explains the mixed evidence on carbon leakage through the different modeling techniques.

Resolution of Data

Besides the variety in the methodological approaches, research also differs with regard to the appropriate resolution level of the regulated entity, the geographical scope, and the time span covered.

The resolution level of the regulated entity analyzed in the literature ranges from the sectoral level, over the firm level to individual plants.

Borghesi et al. (2015), Branger et al. (2016) and Boutabba and Lardic (2017) use sectoral data. Their results might thus underestimate carbon leakage as they ignore carbon leakage within firms, i.e., firms that relocate some of their energy-intensive production from a regulated to an unregulated installation. Klemetsen et al. (2020) therefore use data on the individual installation level. As most investment decisions are yet taken on the firm rather than the installation level itself, the majority of studies aggregate installation data to the firm level.

The studies also differ in regard to the geographical and temporal scope considered: Seven papers reviewed cover multiple countries, while the remaining half researches carbon leakage using data from single countries, i.e., Germany, Sweden, Lithuania, Italy, or Norway. Findings from single-country studies might yet not be easily transferable to the whole EU due to certain country specifics: In Lithuania, for example, firms were strongly oversupplied in Phase I and Phase II, with national installations having a net long position of 15.4 million EUA in Phase I and 10.03 million EUA in Phase II (Jaraite-Kažukauske and Di Maria, 2016). Norway, on the other hand, was only formally linked to the EU ETS in Phase II. Thus, the results shown in Jaraite-Kažukauske and Di Maria (2016) and Klemetsen et al. (2020) might not be representative of the EU ETS region as a whole.

While all studies considered cover at least one year from the second trading period, only five studies (Boutabba and Lardic (2017), Koch and Basse Mama (2019), Makridou et al. (2019) and Carratù et al. (2020) and Klemetsen et al. (2020)) have an extended data set that also covers part of the third trading period. It should be noted that from the four studies that find some evidence of carbon leakage, three studies entail data from 2013 and beyond. Thus, there is some indication that the difference in the time span covered, is a factor that could explain the mixed results.

From the discussion provided above, it can be concluded that there is no evidence that large-scale carbon leakage took place during earlier ETS phases or that the ETS negatively affected the economic performance of firms. However, papers that analyze the international competitiveness of regulated firms show that the FDI in countries with less stringent environmental policies increased. While the size of this effect is small, increasing FDI can be an early warning signal that carbon leakage might occur in the future. Further, studies that use an extended data set that also covers the third EU ETS phase, find evidence for carbon leakage at least within some industrial sectors.

2.4. Determinants of Carbon Leakage

While most studies assessed find no evidence of carbon leakage in the past, this could simply be an indication that the carbon leakage regulation was successful. Thus, in this section, I discuss which factors drive carbon leakage and which regulatory instruments were likely able to prevent large-scale carbon leakage in the past.

To assess determinants that drive carbon leakage, the explanatory variables used in the studies are categorized and discussed. It becomes visible that some industries are more likely to be negatively affected by EU ETS policies than others. Besides sector-specific characteristics, literature also points to market characteristics, such as allowance allocation and EUA prices. Therefore, in the following, the main determinants of carbon leakage, such as sector-specific characteristics (Section 2.4.1), and regulation and market characteristics (Section 2.4.2), are discussed.

2.4.1. Sector-Specific Characteristics

The literature mainly points to four characteristics that determine the carbon leakage risk of a sector or industry: trade intensity, emission intensity, capital intensity, and mobility.

Borghesi et al. (2020) find that the **trade intensity** of a sector drives the number of subsidiaries set up outside of OECD countries. Further, trade-intensive sectors increased their sales of subsidiaries outside the ETS more than less trade-intensive sectors. The increase in FDI indicates that firms belonging to high-trade sectors relocate production to remain competitive on both domestic and international markets in the future. While the respective firms received free allowances in the time frame considered, the findings suggest that firms fear regulatory changes in the future.

In contrast, Martin et al. (2014) find that a firm's trade intensity did not significantly impact carbon leakage in the past. Instead, they show that the firm's **emission intensity** is the main driver of carbon leakage. While the authors show that the carbon intensity of a firm decreases its profitability, Koch and Basse Mama (2019) do not find evidence that firms with a high carbon or energy intensity actually relocated between 2005-2013, indicating that regulation was successful in the receptive time frame.

Other sector-specific characteristics identified by the literature but not captured by the carbon leakage regulation are the **capital intensity** of production and the **mobility** of a sector: Koch and Basse Mama (2019) find that the capital intensity of an industry significantly impacted a firm's relocation choice. Particularly, industries with low capital intensity increased their FDI outside of the EU by roughly 50% during Phase I-III. This is in line with Ederington et al. (2005) who find that capital-intensive industries are less likely to relocate production due to high fixed costs for their production facilities. Vice versa, industries with little capital input needed for production are more likely to move to countries with less stringent environmental policies. The capital intensity of a sector thus likely reduces its mobility.

A subgroup of particularly mobile firms are MNEs as they can adapt flexibly to changing policies in one host region by moving production to another operation in their international network (Fisch and Zschoche, 2011). However, studies analyzing the behavior of this special subgroup during the past trading periods (see e.g. Moore et al. (2019) or Dechezleprêtre et al. (2019)), do not find evidence that global MNEs with subsidies outside the EU ETS member states relocated production in response to the ETS: Contrarily, global MNEs even increased their EU asset base by 1.3% during 2005 and 2012 (Moore et al., 2019).

2.4.2. Regulation and Market Characteristics

Besides these sector-specific characteristics, literature also identifies "free allocation of allowances, extensive overallocation and EUA prices that stayed at low levels" (Carratù et al., 2020) as key drivers for low carbon leakage rates in the past.

Firms that can fully cover their emissions by free allocation, do not have an incentive to move production offshore. (Borghesi et al., 2015) As discussed in Section 2.2.1, 95% and 90% of allowances were allocated for free during Phase I and Phase II, respectively. Makridou et al. (2019) and Carratù et al. (2020) suggest that the non-negative or sometimes even positive effect of the ETS on profitability found by some of the studies reviewed (e.g. Marin et al. (2018) and Klemetsen et al. (2020)), might be driven by this large share of free EUA. When firms have low abatement costs, they might even reduce their emissions and sell excess allowances at prices above their abatement costs, generating windfall profits.[9] A high cost pass-through to consumers as, e.g. indicated by Chan et al. (2013), is a further potential explanation for the increase in economic performance found by some studies.

Another possible explanation for low carbon leakage rates found in the literature is that EUA prices remained at relatively low levels.

Low EUA prices likely led to a too generous CLL as an average carbon price of 30 EUR/t was assumed for the first two carbon leakage assessments (see European Commission, 2009 & 2014). This means that historically, the carbon leakage assessment overestimated the direct and indirect carbon costs of a sector so that also firms with real carbon costs of less than 30% of their gross value added might have been included on the carbon leakage list.

Figure 2.2.: EUA future prices Phase I - Phase IV
Own representation based on data provided by Ember (2021).

[9]No evidence of windfall profits was found for Phase III when the allocation of free allowances switched from grandfathering to benchmarking (Carratù et al., 2020).

Further, Lundgren et al. (2015) argue that historic carbon prices were too low to steer investments into low-carbon technology or trigger carbon leakage. Klemetsen et al. (2020) only find a significant effect of EUA prices on firm performance in Phase II when the average EUA prices were larger than prices in Phase I and the beginning of Phase III. See Figure 2.2 for an overview of historic EUA prices.

Makridou et al. (2019) find that the EUA price did not statistically significantly impact the profitability of firms in the past at all. One reason for this finding could be the high cost pass-through to consumers, i.e., marginal revenue and marginal costs increased almost likewise (Klemetsen et al., 2020). Chan et al. (2013), for example, find that the revenues in the power sector increased when allowances were distributed for free at the beginning of the ETS. Other empirical results also show significant cost pass-through rates for various products in the cement, and iron and steel sectors (Cludius et al., 2020).

It should be noted that the carbon leakage risk is not influenced by the absolute price level but by the carbon price difference in comparison to other countries (Dechezleprêtre et al., 2019). So far, 46 countries and 32 subnational jurisdictions have implemented some sort of carbon pricing, covering 22% of global greenhouse gases (World Bank, 2020). With EUA prices in the first three trading periods being relatively low, ranging from 0 EUR/t to 32 EUR/t, with an average monthly future price of roughly 13 EUR/t in Phase II and Phase III, the price difference to carbon prices abroad was fairly modest as carbon taxes worldwide ranged from 1 Eur/t in the Ukraine to 33 EUR/t in South Korea (World Bank, 2020).

2.5. Implications for Phase IV

The previous assessment shows that sector-specific characteristics and the carbon leakage regulation likely impacted a firm's risk of carbon leakage in the past. In the following, I discuss whether those factors drive the carbon leakage risk for Phase IV.

While literature suggests that sector-specific characteristics influence a firm's carbon leakage risk, there is only little indication that the carbon leakage risk in Phase IV will be substantially different based on the respective determinants. However, increasing prices and changes in the regulatory framework, namely the new carbon leakage criterion, might significantly change the carbon leakage risk for Phase IV. Thus, in the following, I first assess how the carbon leakage risk might evolve in Phase IV given that previous literature focused on ETS phases where EUA prices were low (see Section 2.5.1). I then discuss if the new CLL adequately prevents carbon leakage in Phase IV while maximizing the auction share (Section 2.5.2).

2.5.1. Free Allowances and EUA Prices

From 2026 onwards, free allowance allocation for firms not covered by the carbon leakage criterion will gradually phase out. Instead, firms in sectors not included on the CLL, will need to auction their EUA. The findings by Makridou et al. (2019) show that the share of allowances that needs to be purchased via auctioning, decreases the firms' profitability. This is in line with economic intuition, as larger auction shares translate into higher marginal costs. Thus, the carbon leakage risk for sectors not covered by the CLL might increase.

Another important determinant of a firm's profitability is the carbon price. With substantially larger EUA prices at the beginning of Phase IV (e.g. the EUA price in May 2021 was more than 50 EUR/t), the carbon price difference to countries with lower or no carbon taxation grows. Even if the current price spike is only a temporary high, there is reason to believe that prices in Phase IV and beyond will be substantially higher than in previous periods when EUA were more abundant: Jaraite-Kažukauske and Di Maria (2016) argue, among others, that during Phase I and II, the National Allocation Plans of the member states allocated more allowance than needed to their respective national installations. Further, due to the economic recession in 2008 and 2009, the allowance demand was lower than expected, causing a "large surplus of emission allowances" (European Commission, 2014a). Overallocation and low demand jointly translated into low allowance prices in the past. As policy makers aimed to reduce this historic built-up through allowance backloading (see European Commission (2014c), the introduction of the MSR and the tightening of the allowance cap for Phase IV through the increase of the LRF and the implementation of the CM, average EUA prices in Phase IV will likely remain above historic levels and even further increase in the future.

It can be concluded that the auction share and prices in Phase IV are expected to grow, likely increasing the carbon leakage risk in Phase IV among firms not included on the CLL.

2.5.2. New Carbon Leakage List

In Phase IV, a total of 50 four-digit NACE sectors are listed on the carbon leakage registry, whereof 43 stem from the Manufacturing Sector (NACE 1000-2400) while the remaining seven are in the Mining and Quarrying Sector (NACE 0500-0900). While three four-digit industries[10] have been added to the new list, 100 industries from 21 two-digit NACE sectors were removed. In particular, all sectors that manufacture computers, electronics, machinery, vehicles, other transportation equipment and furniture[11] are completely deleted from the carbon

[10] Manufacture of veneer sheets and wood-based (1621), manufacture of industrial gases (2011) and manufacture of other non-metallic mineral products n.e.c. (2399).

[11] NACE sectors 2500-3200.

leakage list. Further, most subsectors in the manufacturing of textiles, apparel and leather products[12] are no longer included. A full list of changes on the two-digit NACE level is included in Table A.1 in the Appendix.

As the European Commission aims to maximize the auction share, only sectors with a high risk of carbon leakage should be included on the new CLL. Yet, it needs to be ensured that the risk of carbon leakage is minimized. In the following, I thus assess, if the new CLL adequately addresses the determinants of carbon leakage to prevent carbon leakage in Phase IV. Then, I analyze if the new CLL is still too generous.

Can the Carbon Leakage List Prevent Carbon Leakage in Phase IV?

As discussed in Section 2.4, the carbon leakage regulation, namely free allowance allocation for sectors included on the CLL, likely limited carbon leakage in Phases I-III. As the CLL was substantially reduced for Phase IV, the carbon leakage risk for sectors removed from the list needs to be reassessed.

The new carbon leakage criterion led to a substantial reduction of manufacturing industries qualifying for free allowance allocation. Yet, the manufacturing sector is in comparison to other sectors such as the mining and quarrying sector or the power sector[13] found to be fairly mobile across countries (Borghesi et al., 2020). The findings discussed in Section 2.4.1 show that mobility is an important determinant for a firm's decision to relocate. Koch and Basse Mama (2019) analyze the foreign direct investments of German firms regulated by the first two CLL and find that a subset of manufacturing firms in the electrical equipment, machinery and automotive sectors[14] increased their FDI activity outside the EU by over 50%. These sectors are rather mobile as they have a relatively low capital intensity in production.[15] The shifting of assets likely continues in Phase IV, as the respective sectors received free allowances in previous phases but do no longer qualify for free allocation in Phase IV.

With 81, 103, 106 and 186 thousand Euros of gross fixed assets per employee[16], firms in the sectors manufacturing of fabricated metal products, manufacturing of furniture, manufacturing of computer, electronic and optical products and manufacturing other non-metallic mineral products[17] also exhibit a comparably

[12] NACE sectors 1300-1500.
[13] Due to its immobility, the power sector, therefore, needs to purchase all of its EUA on secondary markets since 2013 and is completely exempt from free allowances allocation (European Commission, 2021b).
[14] These sectors correspond to the two-digit NACE codes 2700, 2800 and 2900.
[15] The gross stock of fixed assets per employee in these sectors in Germany in 2006 was 98, 95 and 175 thousand EUR, respectively (Löbbe, 2009).
[16] Own calculation based on the data provided in Löbbe (2009)
[17] NACE codes 2500, 3100, 2600 and 2300, respectively.

low capital intensity.[18] Even though literature identifies capital intensity as a driving factor of carbon leakage, it is not considered in the carbon leakage criterion. Thus, the respective sectors are no longer included on the carbon leakage list. As firms will have to auction their needed allowances in Phase IV, their marginal costs will increase, likely leading to a relocation of the respective production plants. A list of the sectors included on the CLL in Phase II & III, Phase IV, their estimated capital intensity (based on the estimates provided for German industrial sectors by Löbbe (2009)) and their emissions in 2019 is shown in the Appendix (Table A.1).

While the list of sectors discussed above is non-exhaustive, there is some evidence that carbon leakage will increase as some sectors with a low capital intensity are removed from the CLL. Yet, it should be noted that these sectors are rather small emitters in the EU ETS, as the emissions from all sectors removed from the CLL accounted for less than 2.5% of the overall emissions in 2019 (Eurostat, 2021). Thus the absolute carbon leakage effect from these sectors is comparably small.

Is the Latest Carbon Leakage Criterion Too Generous?

In order to increase the auction share and decrease the compensation costs for policy makers, the CLL should be kept as short as possible. Previous studies have found that the same amount of relocation risk induced by the previous CLL could have been achieved with a smaller fraction of free allowance allocation (Martin et al., 2011). As a low share of free allocation and a high share of allowance auctioning was found to increase the dynamic efficiency of the EU ETS, this section analyzes if there is an overallocation of free allowances in Phase IV for certain sectors.

While the CLL was substantially shortened, more than six billion allowances are yet expected to be allocated to vulnerable sectors for free during Phase IV (European Commission, 2021b). This is equivalent to 39% of all allowances supplied over the course of the trading period. Most of the emissions covered by free allowance allocation stem from a small number of energy-intensive sectors. The reviewed literature hereby especially points to the iron and steel production (both captured in the sector "Basic Metals"), cement and lime manufacturing (belonging to "Non-Metallic Mineral Products"), and the pulp and paper industries ("Paper and Paper Products"). Thus, in the following, special focus is put on these high-emitting sectors:

[18]For comparison, gross fixed assets per employee are 224 and 845 thousand Euros, for the pulp and paper sector (1700) and for the manufacturing of coke and refined petroleum products (1900).

No evidence of carbon leakage and increasing FDI was found for firms belonging to the sector *Basic Metals*[19] (see Chan et al. (2013), Branger et al. (2016) and Koch and Basse Mama (2019)). The largest share of emissions in this sector stems from the production of iron and steel which were solely responsible for 7.2% of overall EU ETS emissions in Phase III (European Environmental Agency, 2021). During the latest revision of the CLL, only the subsector ”precious metal production” has been excluded from the list, while all other subsectors are still subject to free allowance allocation.

Despite the large energy intensity of the sector and the correspondingly high carbon costs, Wagner and Timmins (2009) argue that steel producers likely do not relocate as they benefit from their proximity to the domestic market and the advanced technology and agglomeration effects in their traditional location (e.g. the Rhine-Ruhr area). The fairly high capital intensity of 270 thousand Euros per employee points in a similar direction. However, the steel sector features a relatively high trade openness (Burtraw et al., 2010). If domestic companies are no longer subject to free allowance allocation, their competitiveness will decrease. While Europe’s steel trade was mostly balanced in Phase I and Phase II, steel net imports increased since 2015, with Russia, Turkey and the Ukraine being the largest importers of steel to the EU (International Trade Association, 2019). With the Ukrainian carbon tax of less than 1 EUR/t and no carbon price in Turkey and Russia at all (World Bank, 2020), even a modest EUA price imposed on steel producers in the ETS might thus increase net imports further, triggering carbon leakage via the trade-effect channel in an energy-intensive sector. This suggests that free allowance allocation for the production of basic metals needs to continue or a carbon tax border adjustment for steel imports needs to be implemented, to impede large scale carbon leakage from the basic metals sector in the future.[20]

Another large-scale emitting sector in the EU ETS is the *Non-Metallic Mineral Products*[21] sector. In the past, 16 of its four-digit subsectors were included on the CLL. In Phase IV, six of these subsectors do no longer qualify for free allocation. However, all of the large emitting subsectors, such as manufactures of cement, lime, glass and ceramics, that were responsible for more than 11% of the overall EU ETS emissions in Phase III and used almost a quarter of all freely allocated allowances (European Environmental Agency, 2021), are still included on the list.

Chan et al. (2013) and Borghesi et al. (2015) find do no evidence of carbon leakage in the cement industry in previous trading periods. Further, Koch and Basse Mama (2019) do not find evidence that the FDI of firms in the overall sector (2300) increased, arguing that there is no indication that firms in the industry are planning to relocate.

[19]NACE sector 2400.

[20]It should be noted that this is no longer needed if international climate change agreements establish a global carbon price or a global emission trading scheme.

[21]NACE sector 2300.

The capital intensity of firms in the non-metallic mineral sector, measured in gross stock of fixed assets per employee, is with 186 thousand Euros lower than the average capital intensity of manufacturing firms overall (Löbbe, 2009). While this might suggest that the sector is relatively mobile, Branger et al. (2016) argue that high transportation costs decrease the sector's mobility as firms need to stay close to their customer base. While, e.g the cement production, is very carbon-intensive, the sector is only moderately open to international trade (Burtraw et al., 2010), with trade volumes with countries outside of the EU ETS of less than 10% (Sato et al., 2015). The historic evidence and the sector-specific characteristics suggest that the sector is not as vulnerable as determined by the latest carbon leakage assessment.

Lastly, Lundgren et al. (2015), Löschel et al. (2019) and Koch and Basse Mama (2019) point out the importance of emissions stemming from the pulp and paper, and paperboard industries. Both subsectors belong to the sector *Paper and Paper Products*[22], are included on the latest CLL and are jointly responsible for more than 1% of the CO_2e within the EU ETS in 2019 (Eurostat, 2021).

There is neither evidence that the EU ETS impacted the productivity of firms in the Swedish pulp and paper industry between 2005 and 2008 (Lundgren et al., 2015), nor do the empirical findings of Koch and Basse Mama (2019) suggest that German MNEs in the pulp and paper sector are more likely to relocate than firms in other sectors. The results shown in Löschel et al. (2019) even suggest that the EU ETS significantly increased the economic performance of regulated firms in the respective sector. Further, regulated pulp and paper manufacturers were more efficient than the unregulated control group in Phase I and Phase II.

The empirical evidence yet only holds for a time span when the pulp and paper industry was overallocated, as they received more free allowances than needed. The Swedish pulp and paper industry, for example, had an allowance surplus worth 26 million Euro and 58 million Euro, in Phase I and Phase II, respectively (Lundgren et al., 2015). Thus, more research is needed to identify if the sector did not undergo carbon leakage in the past due to low mobility and low trade volumes or simply because the CLL was effective in avoiding carbon leakage through the allocation of free allowances.

The discussion above suggests that the CLL could potentially be further reduced without increasing the risk of carbon leakage. Future research should thus evaluate the carbon leakage risk of the sectors still included on the list. Special attention should hereby be paid to the mobility of a sector, especially of the largest emitting sectors, i.a. Basic Metals, Non-Metallic Mineral Products, and Paper and Paper Products which jointly received roughly 45% of the freely allocated allowances in Phase III.

[22]NACE code 1700.

2.6. Conclusion

The chapter reviewed the empirical literature on carbon leakage in the EU ETS. It can be concluded that the majority of peer-reviewed studies do not find evidence of carbon leakage in the EU ETS. Yet, studies that cover data from Phase III or focus on sectors with low capital intensity and/or high trade volumes find that regulated firms increased their FDI in countries outsides of the EU. This could be an early warning sign for carbon leakage in the future.

However, the empirical results need to be interpreted with caution: as the studies are not able to measure a potential shift of emissions directly, they rely on proxies, such as economic performance, foreign investments and trade relations. The quantitative assessment of these response variables is likely not able to capture carbon leakage in the EU ETS to the full extent. Furthermore, most studies focus on a phase with low EUA prices and more than 150 industrial sectors included on the carbon leakage list. However, the carbon leakage criterion which determines vulnerable sectors that receive free allowances became more restrictive from 2021 onwards. Additionally, current EUA prices of 50 EUR/t are above historic prices and the average price of 30 EUR/ t assumed in previous carbon leakage assessments. In light of these changes, this chapter assessed which sector-specific determinants drive carbon leakage and which regulatory rules likely mitigated the carbon leakage risk in the past.

Despite the limitations of the methodological frameworks used by empirical studies, it can be argued that carbon leakage regulation, such as free allowance allocation, allowance overallocation and correspondingly low carbon prices, likely prevented carbon leakage in the past. Increasing auction shares and higher EUA prices in Phase IV could thus increase carbon leakage rates in the future. Further, sector-specific characteristics determine carbon leakage. While the trade and carbon intensity of a sector is still captured by the new carbon leakage criterion in Phase IV, sectors that only fulfill one of these criteria, are removed from the list. Further, many manufacturing sectors do no longer qualify for free allowances. As some of these sectors are fairly mobile due to low capital intensity, they might choose to relocate in the future.

Despite the substantial reduction of sectors qualifying for free allowance allocation, the share of emissions covered by the CLL did not decrease in the same magnitude because all large-scale emitting sectors are still included on the list. There are mixed indications if the CLL could be even further reduced without significantly increasing the risk of carbon leakage:

As studies covering the Paper and Paper Product sector only cover single countries and are limited to data from the first and second trading period, no implications can be drawn from the existing literature with regard to the free allowance allocation to the respective sector. Literature does not find evidence of carbon leakage in the Basic Metal sector in the past. Yet, especially the iron and steel subsectors are fairly trade intensive. This suggests that the CLL was likely effective in avoiding large-scale leakage from this industry and the sector is rightly exempt from auctioning in Phase IV.

While the cement sector has fairly low trade volumes due to high transportation costs, it has been included on the CLL due to its high carbon intensity. However, the cement industry is found to be rather immobile. Thus, the latest CLL is potentially too generous in allocating free allowances to firms in the cement industry.

As the current carbon leakage criterion is the product of trade and emission intensity, sectors with a moderate to low trade intensity are still included on the list if their emission intensity is very high. This, however, ignores that some sectors have a high capital intensity and/or high transportation costs and are thus fairly immobile. These sectors receive free allowances, even if the risk of carbon leakage is considerably low.

Against this background, the current carbon leakage criterion should be reassessed.

In order to identify the risk of carbon leakage for Phase IV and to make policy recommendations on how the carbon leakage assessment could be improved, future research is needed. Particularly, empirical evidence is needed for Phase III and beyond. To avoid confounding variables and to account for internal carbon leakage within firms and heterogeneity among industries, studies should be conducted for individual firms on the four-digit sectoral level. Special attention should hereby be paid to the impact of EUA prices and the subsector's trade intensity and mobility.

As higher EUA prices and a higher auction share likely increase the risk of carbon leakage in Phase IV, policy makers need to ensure that this risk does not materialize.

3. The Reformed EU ETS - Intertemporal Emission Trading with Restricted Banking

3.1. Introduction

In 2005, the EU ETS was introduced as a cornerstone of the EU climate policy (European Parliament and the Council of the European Union, 2003). While many regions (e.g., California, Australia, Japan) have established other functioning carbon markets since, the EU ETS remains the largest one yet. It covers emissions from energy-intensive industries, the electricity sector and inner-European aviation in 31 countries and accounts for 45% of the total EU greenhouse gas (GHG) emissions.

An emission allowance market coordinates abatement among firms, allocating abatement to firms with low and allowances to firms with high abatement costs (e.g., Tietenberg (1985) and Salant (2016)). The environment's capacity to absorb emissions without harm can be thought of as a finite and hence exhaustible resource. This is depicted in current emission trading schemes by the finite number of emission allowances issued to the market. The well known economic theory on exhaustible resources (e.g., oil exploration) is the model developed by Hotelling (1931). Thereby, the market price of emission allowances develops with the interest rate if unrestricted banking and borrowing of allowances, i.e., saving unused allowances for the future and shifting future emissions to the present respectively, is allowed. This enables emission markets to reach dynamic effectiveness.

The Hotelling model was first used in the context of emission trading systems by Rubin (1996). In his seminal paper, Rubin (1996) sets up a dynamic optimization model, where heterogeneous firms minimize their abatement costs given predefined market rules. An intertemporal market equilibrium exists and is cost-effective when firms minimize their costs intertemporally through banking or borrowing. However, nation states are implicitly required by international climate agreements such as the Kyoto Protocol to refrain from allowing borrowing in the design of emission trading systems (UNFCCC, 2000). The UN hereby discourages nation states to sell future allowances and then dropping out of the agreement.[23] This restriction may create short-run scarcity in the market, leading to a deviation from the original Hotelling price path. Chevallier (2012) applies the theoretical model developed by Rubin (1996) to the EU ETS and discusses the impact of those restrictions on banking and borrowing given the prevailing EU regulation at that time.

The regulatory framework of the EU ETS has been subject to multiple changes since then. The latest major amendments have been the increase of the Linear Reduction Factor (LRF), the introduction of the Market Stability Reserve (MSR) and the option to cancel allowances from the MSR, referred to as Cancellation Mechanism (CM). In October 2014, EU leaders adopted the 2030 climate and energy framework for the European Union. This framework comprises i.a. the target of at least 40% GHG reduction in 2030 compared to 1990 levels. To meet this target, the annual reduction of issued allowances in the EU ETS was increased from a LRF of 1.74% in the third trading period (2013-2020) (European Parliament and the Council of the European Union, 2003) to a LRF of 2.2% from 2021 onwards (European Parliament and the Council of the European Union, 2018).

In January 2019, the MSR came into force. Its intended effect is the strengthening of short-run carbon prices in the EU ETS. These were considered to not sufficiently spur investment in low-carbon technologies due to the perceived allowance surplus in phase 3 (European Parliament and the Council of the European Union, 2015). The MSR is a public deposit fed with allowances from the auction volume, whenever the number of allowances in circulation exceeds a certain threshold (European Parliament and the Council of the European Union, 2015). From 2023 onwards, the volume of the MSR is limited to the previous year's auction volume. Allowances in the MSR exceeding this upper limit are invalidated by the CM (European Parliament and the Council of the European Union, 2018).[24]

Recent contributions by Richstein et al. (2015), Perino and Willner (2016) and Beck and Kruse-Andersen (2020) evaluate the impact of the MSR on price and emission paths. Perino and Willner (2016) and Richstein et al. (2015) find that the MSR itself impacts the market price only temporarily and increases price volatility, contrary to its intended purpose. Because the aggregated emission cap is not altered, the MSR is considered allowance preserving. In Perino and Willner (2017) the impact of an exogenous, one-time cancellation of 800 million

[23] Another reason for this restriction is the shape of global damage curves. Since most scholars (e.g., Rubin (1996)) assume that pollution damage functions are convex, early emissions cause greater environmental damage than delayed emissions, thereby requiring a limitation on borrowing.

[24] This paper refrains from the fact that the European Commission and member states will review the final cancellation of allowances (European Parliament and the Council of the European Union, 2018) which introduces uncertainty about whether allowances will be cancelled at all. The first review is scheduled for 2022, further reviews of the MSR and the CM will take place in five-year intervals afterwards (European Parliament and the Council of the European Union, 2015).

allowances is discussed. However, the newly introduced CM decreases the overall emission cap endogenously, i.e., the cancellation depends on the number of allowances in the MSR and thus on the banking decision of the firms.

The original version of the Hotelling model uses a continuous representation of time due to the continuity of fossil fuel extraction. Continuous time models are also used in, e.g., Perino and Willner (2016) and Perino and Willner (2017). This continuous representation of time, however, is not an accurate representation of the EU ETS with the MSR and CM. Clearing of allowances, intake and reinjection of the MSR and the cancellation volume are determined on a yearly basis. Consequently, this paper proposes a discrete time structure to accurately represent current EU ETS regulation.

A discrete time model has also been used by Beck and Kruse-Andersen (2020) who evaluate the impact of national policies in light of the reformed EU ETS with MSR and CM and calibrate their discrete time models to historic market outcomes. The authors solve iteratively a firm's profit maximization problem assuming quadratic abatement costs and technological progress of renewable energies. Hereby, they show that the reform of the EU ETS increases allowance prices and decreases emissions in the short and long run. However, long-run effects are found to be substantially higher than in the short run. Further, they find that the effect of national policies on EU ETS emissions strongly depends on the timing of their implementation. If national abatement measures take place before 2023, they potentially increase the cancellation volume and thus reduce total EU ETS emissions.[25] However, their overall evaluation of the EU ETS amendments is ambivalent: While under the new regulation national policies potentially have an impact on abatement within the EU ETS, the complexity of the regulation may hinder the implementation of cost-efficient national policies. Silbye and Sørensen (2019) take a similar approach assessing the effect of national emissions reduction in light of the latest reforms. They find that if national emission reduction policies take place early, unused allowances will be transferred to the MSR and partially cancelled through the CM. If national reduction policies are implemented at a later point in time, they do not trigger an additional MSR intake and will therefore have no lasting effects on emissions.

The contribution of the paper at hand is threefold: Firstly, we develop a model which incorporates the current EU ETS regulation accurately, namely the change in the LRF and the introduction of the MSR and the CM. The volumes of the MSR and the CM are endogenously determined within a closed-form solution. In particular, the decision algorithm of the EU ETS operates on an annual basis. Therefore it is depicted in a discrete time model. Secondly, the decomposition of the recent amendments into its single components facilitates a better understanding of the underlying economics. This allows us to identify the main price drivers in the market. The sensitivity analysis validates the robustness of the model results and determines which economic effects can be expected

[25]This effect is also found and discussed in Carlen et al. (2018).

under various regulatory scenarios and parameter assumptions. Thirdly, the cost effectiveness of the current EU ETS regulation is compared with theoretical first-best scenarios based on the unaltered Hotelling model. Thereby, we can draw conclusions on the economic implications of the different regulatory instruments by discussing their individual impact on the economic performance.

The remainder of this paper is organized as follows: Section 3.2 develops the model, including the dynamic optimization problem of the firm and the equilibrium conditions in a competitive market given current EU ETS regulation. In section 3.3, the functioning of the model is explained and validated by sensitivity analyses. Further, the underlying economic effects are decomposed. Section 3.4 discusses the implications of the three amendments individually and assesses the cost effectiveness of the new regulation. Section 3.5 concludes.

3.2. Discrete Dynamic Optimization Model

We model the decision making of N polluting firms within the intertemporal market for emission allowances, namely the EU ETS, which is assumed to be perfectly competitive. In the following section, we describe our model which covers the individual decision making on the firm level. In section 3.2.2 the market clearing and equilibrium conditions are derived from the individual optimality conditions. The MSR and the CM are modelled in section 3.2.3 as an exact replication of the current EU regulation. The parameters used for the numeric illustration are presented in section 3.2.4.

3.2.1. Decision-Making of a Representative Firm

We assume a rational firm with perfect foresight which aims to minimize the present value of its total expenditure

$$PV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} C(e(t)) + p(t)x(t). \tag{3.1}$$

In each discrete time period $t = 0, 1, \dots, T$ the expenditure consists of two parts: the abatement costs $C(e(t))$ and the costs of acquiring of allowances $p(t)x(t)$. The firm can decide on the variables $e(t)$ for yearly emissions and $x(t)$ for yearly acquisition or sales of allowances. In line with Rubin (1996), we assume that the abatement costs follow a quadratic and convex function of the form $C(e(t)) = \frac{c}{2}(u - e(t))^2$. The baseline emission level u and the cost parameter c are exogenously given. Due to the assumption of a perfectly competitive market for allowances, the allowance price $p(t)$ is not influenced by the individual decision of the firm. The yearly costs are discounted at an annual interest rate of r. Let T be the first point in time when no further allowances are issued and all issued allowances are depleted. Hence, for all $t \geq T$ an emission cap of zero is established which makes allowance trading redundant.

As discussed in the previous section, the EU ETS enables firms to bank allowances for later use. This linking between time periods is modelled with the decision variable $b(t)$, which is the volume of acquired allowances in the private bank of the individual firm in period t. As intertemporal borrowing is prohibited, we require $b(t) \geq 0$. Additionally, in each time period the change in the bank $b(t) - b(t-1)$ has to be equal to the difference of net acquisition of allowances $x(t)$ and emissions $e(t)$.[26]

Combining the expenditure minimization with the intertemporal banking constraint yields the optimization problem for the individual firm

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t} [\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\ & s.t.\ b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = 1, 2, \dots, T \\ & \qquad b(t) \geq 0 \\ & \qquad x(t),\ e(t) \gtrless 0. \end{aligned} \tag{3.2}$$

We assign the Lagrange multipliers $\lambda(t)$ and $\mu_b(t)$ to the flow constraint and the positivity constraint, respectively. As the optimization problem is convex and fulfills the Slater condition, the KKT conditions are necessary and sufficient for optimality.[27] These imply that $\mu_b(t)$ is 0 if $b(t)$ is positive.

From the optimality conditions we get

$$c(u - e(t)) = p(t). \tag{3.3}$$

This states that the firm will set emissions $e(t)$ such that the marginal abatement costs equal the price $p(t)$. Economically speaking, the firm expands emissions $e(t)$ and acquires allowances $x(t)$ whenever the allowance price is below the marginal abatement cost. Contrary, the firm abates more emissions if the allowance price exceeds the marginal abatement costs.

3.2.2. Market Equilibrium

While the firm's demand for allowances solely depends on the optimization problem stated above, the price is determined by the market. Supply, i.e., issuance

[26] We formally allow emissions to be negative. However, as borrowing is not allowed in the model, negative emissions do not occur.

[27] See Appendix B.1 for details on the Lagrange function and the exact KKT conditions including complementary conditions.

of allowances, and demand, i.e., the firm's acquisition of allowances, have to be balanced by the price, such that the market clears.

We define the supply $S(t)$ as the path of issued allowances in period t, which is regulated to be decreasing from an initial value $S(0)$ at a linear rate $a(t)$, hence $S(t) = S(t-1) - a(t)S_0$.[28] The issued allowances are partially auctioned ($S_{auct}(t)$) and partially distributed for free.[29]

The price path $p(t)$ is determined in the market such that aggregated emissions over time are smaller than aggregated issued allowances. This is

$$\sum_{\tilde{t}=0}^{t} e(\tilde{t}) \leq \sum_{\tilde{t}=0}^{t} S(\tilde{t}) \text{ for all } t = 0, 1, \ldots, T.$$

We assume that firms are homogeneous. From the individual optimality conditions stated in the previous section, we derive the rule for the development of market prices

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \tag{3.4}$$

Economically speaking, whenever the private bank $b(t) > 0$, the corresponding shadow costs are $\mu_b(t) = 0$ and hence the price rises with interest rate r. This is in line with the continuous model in Hotelling (1931), where the optimal emission path can be achieved if banking and borrowing is possible. If at some point in time $\tau_{b=0}$ the bank becomes 0, firms would implicitly like to borrow allowances from the future, which is forbidden by EU regulation.[30] Therefore, firms have to abate more than in the optimal emission abatement path before $\tau_{b=0}$. This in turn means that the firm abates less than in the optimal abatement path after $\tau_{b=0}$. Consequently, the price will increase at a lower rate than r after $\tau_{b=0}$.[31]

3.2.3. Introduction of the MSR and the CM

With the introduction of the MSR and the CM the supply of allowances is no longer exogenously determined by the regulator. The amount of auctioned allowances $S_{auct}(t)$ additionally depends on the banking decisions of individual firms. To depict the development of the allowance supply correctly, we define the total number of allowances in circulation $TNAC(t) = \sum_{i=1}^{N} b_i(t)$, where b_i represents the individual banking decision of firm i.

[28] S_0 represents the number of allowances in 2010. $a(t)$ is the LRF.

[29] Following EU Directive 2018/410 the share of auctioned allowances is 57%, i.e., $S_{auct}(t) = 0.57\, S(t)$.

[30] We disregard the unlikely case that it could be possible that the path of issued allowances coincides with the optimal emission path. Hence, the bank would be 0 for all t.

[31] If at a later point in time a second banking phase occurs, the Hotelling rule becomes valid again.

The MSR mechanism works as follows: If at some time t the $TNAC(t)$ exceeds an upper limit ℓ_{up}, the number of auctioned allowances will be reduced by a share $\gamma(t)$ of the TNAC of the previous year. This reduction of auctioned allowances is inserted into the MSR. If $TNAC(t)$ drops below a lower limit ℓ_{low}, R allowances from the MSR are auctioned additionally.[32]

The CM states that allowances will be cancelled from the MSR, i.e., become invalid if the number of allowances in the MSR exceeds the auction volume of the previous year (European Parliament and the Council of the European Union, 2018).

These two amendments to the EU ETS are accurately expressed by

$$S(t) = S(t-1) - a(t)S_0 - Intake(t) + Reinjection(t). \tag{3.5}$$

The MSR is then given by

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t), \tag{3.6}$$

with

$$Intake(t) = \begin{cases} \gamma(t) * TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{3.7}$$

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else,} \end{cases} \tag{3.8}$$

and

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \tag{3.9}$$

3.2.4. Model Implementation and Parametrization

The regulatory decision rules and complementary conditions stated are non-linear. For the implementation and solution of the model with GAMS and CPLEX, they are equivalently reformulated as linear constraints using binary

[32] This regulation started in 2019 with an upper limit ℓ_{up} of 833 million and a lower limit ℓ_{low} of 400 million allowances. The intake rate $\gamma(t)$ into the MSR is 24% of the TNAC until 2024 and 12% afterwards. The reinjection takes place at tranches R of 100 million allowances (European Parliament and the Council of the European Union, 2015).

variables and the big-M method. This allows to combine the exact regulatory rules of the EU ETS with the market equilibrium model derived by the optimality conditions of the firms in an mixed integer linear program.

In 2019, the MSR is initially endowed with 900 million allowances which were backloaded between 2014 and 2016 (European Parliament and the Council of the European Union, 2015). Further, allowances that will remain unallocated at the end of phase 3 of the EU ETS are transferred into the MSR in 2020. These are estimated to amount to 600 million allowances (European Commission, 2015). As initial value for the TNAC in 2017 we use 1645 million allowances as published by the European Commission (2018b). The number of issued allowances is calculated based on the 2199 million allowances issued in 2010 (European Environmental Agency, 2018) and reduced on a yearly basis by the corresponding LRF.[33]

Apart from the above mentioned regulatory parameters, the model is fed with further exogenous parameters, namely the interest rate, the baseline emissions and the backstop costs. In section 3.3.2 we discuss how the choice of these parameter values impacts the results. If not stated otherwise, the following values are used in the model: We apply a private interest rate r of 8%, representing the approximated weighted average cost of capital (WACC) of fossil power plants (Kost et al., 2018) and energy-intensive industries (KPMG, 2017). We acknowledge that there is high uncertainty about the baseline emission level in the absence of a cap-and-trade system, e.g., because of technology advancement (Beck and Kruse-Andersen, 2020), economic activity and weather conditions (Borenstein et al., 2018). For the sake of simplicity, we assume constant baseline emissions u of 2000 million tonnes CO_2 equivalent (CO_2e).[34]

We think of the backstop costs as the costs associated with a costly but inexhaustible abatement option, e.g., direct air carbon capture and storage. Assuming backstop costs $\bar{c}$ of 150 EUR/t[35], the cost parameter c is calculated by $c := \bar{c}/u$. By this definition we ensure that the last ton of baseline emissions is abated at backstop costs, i.e., for our quadratic abatement cost function $C'(0) = \bar{c}$.

[33] In our model we assume that without the reform the LRF of 1.74% would have been continuously used. However, the LRF for the time after 2020 had not been defined yet. Likewise, we assume that the increased LRF the factor of 2.2% will be used for all future trading periods. (European Parliament and the Council of the European Union, 2018)

[34] This assumption is similar to Perino and Willner (2016) and Schopp et al. (2015) who use constant baseline emissions of 1900 million tonnes CO_2e and 2200 million tonnes CO_2e, respectively. The sensitivity of this assumption is calculated and further discussed in section 3.3.2.

[35] The backstop costs of 150 EUR/t are in line with medium-range predictions of common Carbon Capture and Storage (CCS) technologies (e.g., Saygin et al. (2012) and Kuramochi et al. (2012)).

3.3. Results and Sensitivity Analysis

With the parametrized model set up above, we are able to assess the development of emissions, prices and MSR movements under the current regulation. Robustness of our results in terms of the parametrization is guaranteed by an extensive sensitivity analysis in section 3.3.2.

3.3.1. Results under the Current Regulation

From Equation 3.4 we know that as long as banking occurs, which is the case as long as sufficient allowances are available, the allowance price increases at the rate of interest (in accordance with the Hotelling rule). Under the current regulation, this development of abatement, emissions and the allowance price takes place until the TNAC is depleted in 2039, as depicted in Figure 3.1. Thereafter, annual emissions equal the number of issued allowances, which decline with the LRF. The allowance price increases at a lower, degressive rate, because marginal abatement costs equal prices (Equation 3.3). When all allowances are used, emissions drop to zero, and the allowance price reaches the marginal costs of the backstop technology (150 EUR/t)[36] and remains at this upper limit. This happens from 2058 onwards.

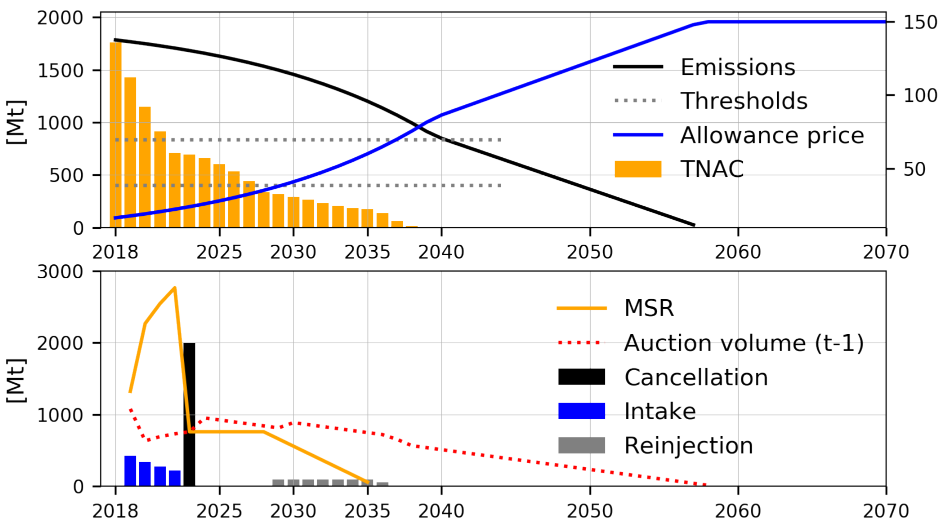

Figure 3.1.: Development of emissions, TNAC, MSR, cancellation and allowance prices

[36]EU ETS regulation imposes a penalty of 100 EUR/t (inflation-adjusted) if firms are non-compliant. The penalty does not release firms from their obligation to surrender allowances (European Parliament and the Council of the European Union, 2003). Therefore, paying the penalty fee is never a rational outcome, independent of the backstop price level.

After the implementation of the MSR in 2019, allowances are inserted into the MSR based on the rules described in section 3.2.3 since the TNAC exceeds the limit of 833 million allowances (see Figure 3.1). Until 2023, the MSR accumulates 2762 million allowances. As the CM enters into force in 2023, allowances become invalid according to the rules described in section 3.2.3. This leads to a one-time cancellation of 2002 million allowances in 2023.[37] This is equivalent to about 5% of all issued allowances from 2018 onwards. In 2028, the TNAC drops below the threshold of 400 million. Thus, from 2029 until the depletion of the MSR in 2037, 760 million allowances are reinjected into the market.

3.3.2. Sensitivity Analysis

As discussed in section 3.2.4, the model uses three exogenous input parameters: backstop costs, baseline emissions and interest rate. Varying these parameters does not change the modus operandi of the model. However, the numerical results are influenced by the assumed parameter values. Therefore, in the following we carry out sensitivity analyses to carve out robust results.

Backstop Costs

Due to the uncertainty when it comes to the realization of specific backstop costs in the future, we analyze its impact in a sensitivity. Ceteris paribus (in particular for a given level of baseline emissions u), a change in backstop costs only shifts the price path, but does not affect the level of emissions, abatement, TNAC, MSR or cancellation. In particular, the point in time at which the TNAC is depleted does not change. This is because the initial quantities still fulfill all equilibrium and regulatory conditions from section 3.2 for a scaled version of the price path. We state and prove this finding formally in B.2.

Baseline Emissions

Since it is not possible to measure baseline emissions, it is essential to take the uncertainty regarding this parameter into account (Borenstein et al., 2018). As the choice of its level has a significant impact on the numerical model results, a sensitivity analysis helps to assess the range of potential outcomes.

If we assume higher baseline emissions then in the standard case from section 3.3.1, the firm has higher emissions and correspondingly lower banking early on (see Figure 3.2). Since this behaviour drives allowance prices up, the firm increases abatement, partially compensating the effect of higher baseline emissions. However, the overall effect on banking remains negative. An increase of baseline emissions from 2000 to 2200 million tonnes CO_2e depletes the TNAC

[37] In this setting cancellation only takes place once. However, this is not inevitable and depends on the parametrization. Thus, multiple cancellation phases are possible.

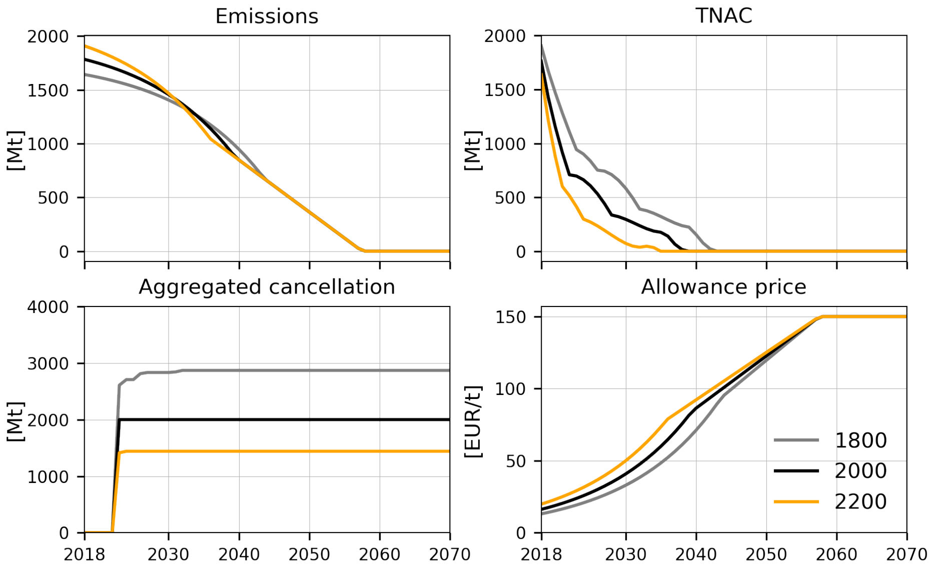

Figure 3.2.: Sensitivity analysis for baseline emissions

four years earlier. By regulation, the decrease of the TNAC leads to a lower intake of allowances into the MSR. Therefore, higher baseline emissions have a twofold negative effect on cancellation: Firstly, the lower MSR intake leads to a lower MSR volume. Secondly, it results in a larger auction volume as the MSR intake is subtracted from the allowances to be auctioned. Additionally, higher baseline emissions require stronger abatement to meet the same emission target. Thus, at any time t, allowance prices are above the ones in the standard case. An increase in baseline emissions from 2000 to 2200 million tonnes CO_2e leads to a price increase by 22% in all years in which the Hotelling rule applies.

Vice versa, lower baseline emissions lead to lower prices, higher TNAC levels and therefore higher intake into the MSR and larger cancellation volumes. Further, TNAC and MSR deplete at a later point in time. However, changes in the baseline emissions impact quantities asymmetrically. If the baseline emissions lie for instance at 1800 instead of 2000 million tonnes CO_2e, about 900 million allowances are cancelled additionally, whereas about 600 million allowances are cancelled additionally if the baseline emissions lie at 2000 instead of 2200 million tonnes CO_2e.

Figure 3.3 assesses the impact of baseline emissions on the aggregated amount of allowances cancelled. The cancellation volume increases overproportionally with a decrease of baseline emissions. In other words, with low baseline emissions, the model reaches higher levels of cancelled allowances. The higher the baseline emissions, the faster the private bank is depleted and thus the lower the MSR and the cancellation volume.

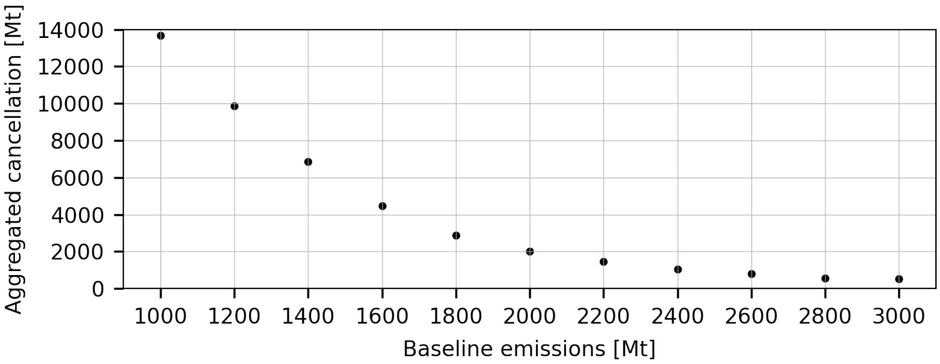

Figure 3.3.: Effect of baseline emissions on cancellation

Over time declining baseline emissions (as assumed by, e.g., Carlen et al. (2018) and Quemin and Trotignon (2018)) require lower abatement efforts. Hence, prices are strictly lower, leading to higher emissions and a lower TNAC in the short run and less cancellation in 2023. As the TNAC and the MSR deplete later, emission levels in the long run are higher compared to the case with constant baseline emissions.

Interest Rate

The interest rate of a firm reflects the opportunity costs of abatement, i.e., the profitability of alternative investments. Therefore, the interest rate impacts the firm's abatement decision directly. Thereby, the emission path and banking decision is affected, finally having an impact even on the MSR and the CM.

Figure 3.4 shows the sensitivity of the model results for interest rates of 3%, 5%, 8% and 16%. With a higher interest rate, the initial price level is lower but increases at a higher rate afterwards. Consequently, firms prefer to delay abatement and therefore increase emissions in the short run. With a similar rationale as in the sensitivity with higher baseline emissions, a higher interest rate leads to fewer MSR intake and less cancellation due to higher emissions in the short run.

In consequence, abatement has to be higher in the medium run to compensate for the initially higher emissions. In our example in Figure 3.4, starting with the depletion of the TNAC in 2030, the emissions in the sensitivity with 16% interest rate are lower than in the standard case with 8%. In the long run after 2040, emissions equal the exogenous supply of allowances in both cases. Hence, the price development is independent of the interest rate.[38]

[38]In both cases the reinjection of allowances from the MSR ends before 2040.

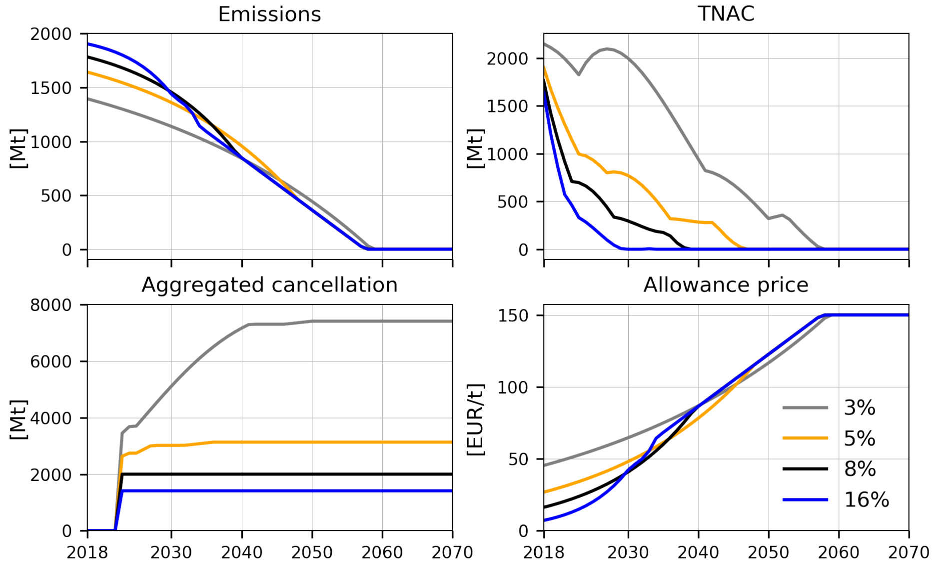

Figure 3.4.: Sensitivity analysis for the interest rate

With a lower interest rate, we can observe the opposite effects. Prices start at a higher level but increase at a lower rate. Emissions decrease in the short run and increase in later periods. A higher TNAC leads to more intake into the MSR and a higher volume of aggregate cancellation. In particular, with a lower interest rate the TNAC is non-empty for a longer time period, which in turn causes the price to longer rise with the interest rate. With an interest rate of 3%, the price rises with the interest rate until 2057.

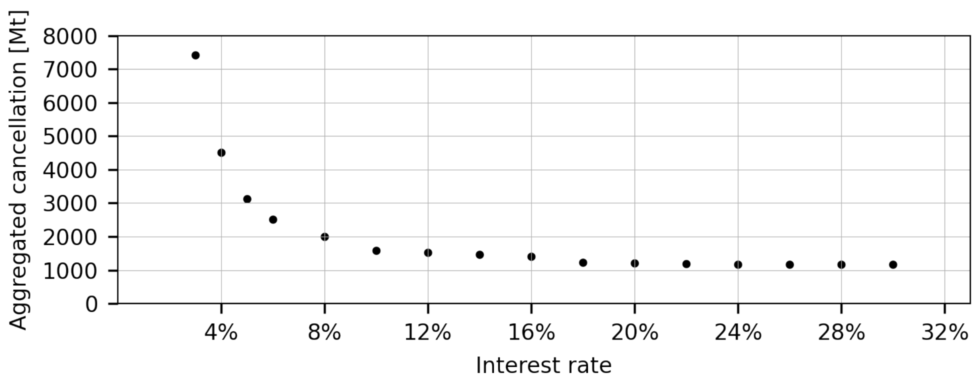

Figure 3.5.: Effect of interest rate on cancellation

Figure 3.5 assesses the impact of the interest rate on the total amount of allowances cancelled. Note that the aggregated cancellation volume and therefore the total abatement only changes significantly for low interest rates. The total number of cancelled allowances cannot fall below a certain level, because the emission level is bounded by the baseline emissions. In other words, the quantity of allowances needed in the short run is limited and therefore some amount of cancellation takes place independent of the interest rate.

Two effects determine the relationship between interest rate and cancellation volume: First, a high interest rate leads to higher emissions and less MSR intake in the short run. Therefore, the cancellation volume in 2023 decreases with the interest rate. Second, as total abatement does not change significantly, a high interest rate leads to higher abatement and a higher TNAC in the medium run, potentially causing more cancellation after 2023. The second effect partially offsets the first effect in terms of the total volume of allowances cancelled.

A high interest rate of firms leads to lower cancellation volumes. Since greater uncertainty in the market is reflected by higher interest rates of market participants, we conclude that the higher the uncertainty perceived in the market, the weaker the impact of the CM.

3.3.3. Results in the Context of Previous Studies

In the following, we put the findings presented in section 3.3.1 in the context of previous studies. Silbye and Sørensen (2019) and Beck and Kruse-Andersen (2020) find that in addition to the cancellation in 2023, further allowances are cancelled during the following years, leading to cumulative cancellation volumes of 5000 million (Silbye and Sørensen, 2019) and 6000 million (Beck and Kruse-Andersen, 2020). The significantly larger cancellation volumes compared to our result can be explained by the underlying model and parameter assumptions: Both studies assume a lower initial baseline emission level which is moreover decreasing over time.[39] As discussed in Section 3.3.2, lower baseline emissions cause the TNAC and the MSR to deplete later (e.g., Silbye and Sørensen (2019) find that the TNAC depletes in 2057, while our model suggests a depletion in 2039) and a larger cancellation volume. Another reason for higher cancellation volumes in Beck and Kruse-Andersen (2020) lies in their assumption of a convex marginal abatement cost curve. Compared to a linear curvature, the convexity assumption increases the TNAC and hence cancellation volumes. Further, Silbye and Sørensen (2019) calibrate their model to depict the price spike in 2018 by the assumption of a decrease in interest rate caused by the reform. They assume a demand elasticity that translates to a significantly higher backstop cost level than in our model.[40] While the backstop price itself does not influence banking behavior and cancellation volume (see Section 3.3.2), it leads to a higher overall price level.

[39] Their assumption of decreasing baseline emissions implies decreasing backstop costs given that the cost parameter is held constant.

[40] Their sensitivity parameter of allowance demand of 2.2 corresponds to an initial backstop cost level of 760 EUR/t. In other words, the initial cost parameter c implied by Silbye and Sørensen (2019) is nine times larger than the one used in Perino and Willner (2017) and six times larger than the one used in our model.

Despite the different modelling approaches, our numerical results are in line with the findings of Carlen et al. (2018) and Perino and Willner (2017). With their iterative solution approach, Carlen et al. (2018) find a one-time cancellation of 2400 million allowances in 2023. The TNAC is depleted in 2034 and the MSR is empty in 2035. Their slightly higher cancellation volume can be explained by their lower interest rate of 2.5% (see section 3.3.2). One of the scenarios from Perino and Willner (2017) depicts a MSR limited by the auction volume. With assumptions on baseline emissions and interest rate close to ours, their results are similar: Their TNAC is depleted in 2037 and their MSR remains empty from 2036 onwards. Thus, despite different modelling approaches, our numerical results (cancellation volume of 2000 million allowances, MSR depletion in 2037 and TNAC depletion in 2039) are in line with those of the two former studies.

3.4. Impact of the EU ETS Amendments on Emissions, Prices and Economic Performance

We assess the impact of the recent EU ETS amendments on abatement paths, total emissions and price paths. The results of the EU ETS reforms presented in Section 3.3.1 are decomposed into the effects of single amendments, namely the increase in the LRF, the MSR and the CM (section 3.4.1). In Section 3.4.2 we evaluate the economic performance of the amendments by comparing the single amendments to hypothetical first-best scenarios with the respective emission cap. Table 3.1 depicts the characteristics of the different scenarios used in this section.

	LRF after 2020	**MSR**	**CM**
pre-reform	1.74%	no	no
increased LRF	2.20%	no	no
MSR	2.20%	yes	no
post-reform	2.20%	yes	yes
late cancel	2.20%	yes	cancellation from the long end

Table 3.1.: Overview of examined scenarios

3.4.1. Decomposition of Effects of the Recent EU ETS Amendments on Prices and Emissions

Apart from the pre-reform scenario and the post-reform scenario that depicts the current EU ETS regulations discussed in section 3.3, we set up the increased LRF scenario (high LRF from 2021 onwards, but no MSR and CM) to isolate the impact of the increased LRF from the aggregated reform results (see Figure 3.6). The results show that the effect of the lower cap on issued allowances is significant: with the higher LRF of 2.2% the total emission cap is reduced by over 9 billion allowances which equals a 21% reduction of the allowance volume issued after 2020. The last allowances will be issued in 2057 and thus 10 years earlier than with the lower LRF.

This additional scarcity also shows in the price difference between the pre-reform scenario and the increased LRF scenario. The higher LRF increases prices at any point in time but the difference is most noticeable in the long run. The change in the LRF does not impact the banking decision of the firm, and thus at which time $\tau_{b=0}$ the TNAC becomes zero and prices develop at a degressive rate. As the price level at time $\tau_{b=0}$ is higher in the increased LRF scenario, the degressive price path after this point develops from a higher level and at a higher rate. Thus, the price increase resulting from the change in the LRF is most significant in the long run.

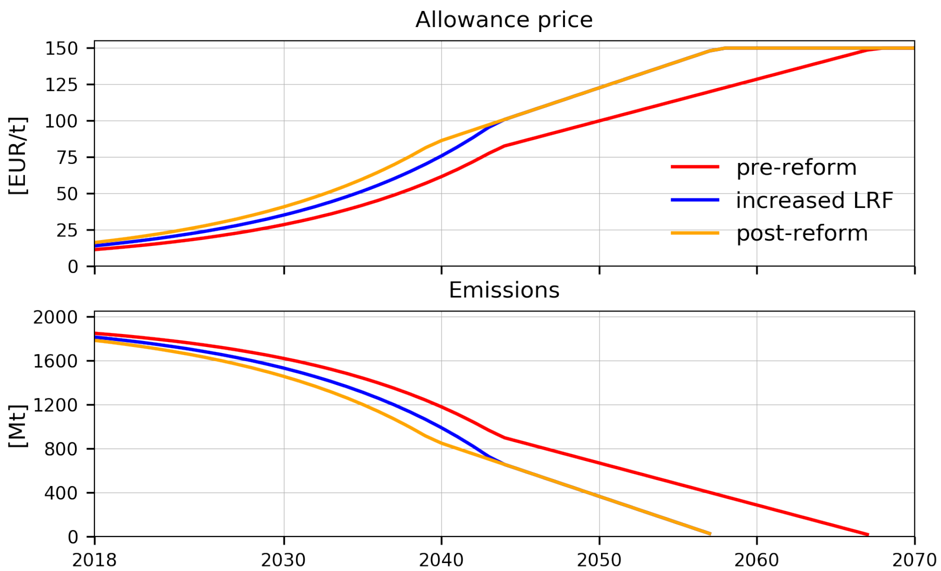

Figure 3.6.: Effect of the change in the LRF

Now, we isolate the effect of the MSR from the change in the LRF, by comparing the introduction of the MSR with the increased LRF scenario. By regulation, the MSR only shifts emissions from the present to the future and thus can be considered an intertemporal smoothing of abatement. This results from storing allowances in the MSR and limiting today's allowance supply, reinforcing abatement in the near future and decreasing abatement later on.

While the intake of allowances in the MSR leads to higher prices in the short run, the reinjection phase reverses this effect in the long run by increasing the auction volume in tranches of 100 million allowances annually compared to the increased LRF scenario. (Figure 3.7). Thus, the MSR remains allowance preserving and does not alter the emission cap itself. This is in line with the findings of, e.g., Perino and Willner (2016) and Richstein et al. (2015).

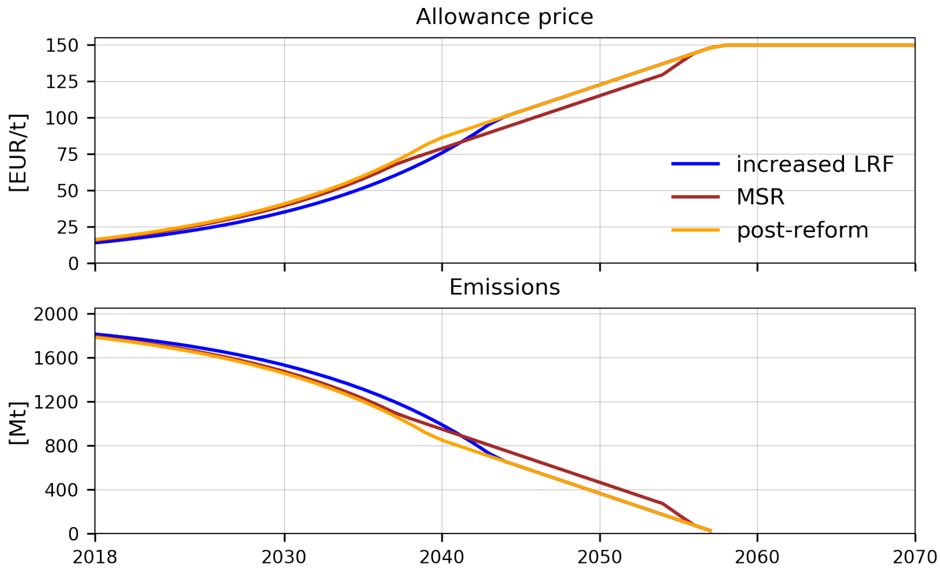

Figure 3.7.: Effect of the MSR and the CM

In contrast, the CM alters the overall emission cap. Thus, fewer allowances are available in the post-reform scenario (including the CM) than in the MSR and increased LRF scenarios. The firms take this into account and choose an emissions path that is slightly lower in the post-reform scenario. Therefore, the overall intake into the MSR is slightly higher than in the MSR scenario. About 2000 million allowances are cancelled in 2023 and the remaining 760 million allowances in the MSR are reinjected into the market from 2029 onwards. The MSR is fully depleted in 2037, i.e., 19 years earlier than in the scenario without the CM. Compared to this MSR scenario, the model reveals only minor price effects of the cancellation in the short term (e.g., 3% price difference in 2030). However, the price difference becomes larger once the MSR is fully depleted in the post-reform scenario and the cancellation causes additional scarcity in the market (e.g., 8.5% price difference in 2040). This finding indicates that while the cancellation takes place at an early time, prices are more affected in the long run.

Conversely, the difference in prices between the increased LRF scenario and the post-reform scenario can only be observed in the short and medium run. Due to the reduced cap and thus additional scarcity in the market, the TNAC depletes at an earlier time $\tau_{b=0}$.[41] Because the MSR is depleted once the TNAC falls below the limit ℓ_{low}, the change in the LRF is the only determining factor causing the higher price path compared to the pre-reform scenario in the long run.

[41] In the increased LRF scenario $\tau_{b=0} = 2042$. This is 4 years later than in the post-reform scenario.

The cancellation volume of 2 billion allowances is significantly smaller than the reduction of 9 billion allowances by the increased LRF.[42] Even though the effect of an increased LRF seems to be well understood by scholars and thus has not been a focus of previous studies, it is important to stress that the increased LRF is the main price driver of the reform.[43]

3.4.2. Cost Effectiveness

In the following, we assess the impact of the reform on the intertemporal economic performance of the EU ETS. Fuss et al. (2018) differentiate between two frameworks for its assessment: Dynamic cost efficiency and dynamic cost effectiveness. Dynamically efficient policies maximize welfare by minimizing the social cost of emission abatement and damages. Those damage costs are commonly referred to as social costs of carbon (SCC). Since the SCC strongly vary with location, time preferences and other underlying factors, the estimates depicted in literature cover a broad range of potential values. Tol (2019) estimates today's global SCC to range from 14 EUR/t carbon to 55 EUR/t carbon, Cai and Lontzek (2018) argue that the SCC can raise to as much as 667 EUR/t carbon by 2100. Given the high uncertainty regarding the SCC and its importance for determining cost efficiency, we follow Fuss et al. (2018)) by refraining from using this framework and instead focus on the concept of dynamic cost effectiveness. This framework assesses whether predefined quantity targets are reached by the lowest aggregated abatement costs without further consideration of external costs of emissions. The design of the EU ETS itself targets cost effectiveness. Allowance supply is predefined such that the system only minimizes the abatement costs.[44]

Figure 3.8 gives an overview of discounted abatement costs and emission levels of the different scenarios. The cost-effective frontier depicts the minimal discounted abatement costs for the respective emission level. This is achieved by a hypothetical scenario in which firms can allocate allowances in time without any intertemporal restriction. The discounted abatement costs are normalized to the discounted abatement costs of the cost-effective abatement path for the emission level where the post-reform allowance supply is fully exploited.

[42] This finding is also depicted in Appendix B.3 where we compare the effect of the CM in the post-reform scenario with a post-reform scenario with the pre-reform LRF of 1.74%.

[43] A survey conducted in 2018 revealed that there are common misconceptions about the main price driver of the reform. Experts from the field expressed their intuition about the main price driver of the allowance price. Only 21% of the respondents named the increased LRF as the main reason for the price increase, while 34 % considered the CM as the main price driver (see Wölfling and Germeshausen (2019)).

[44] A cost-efficient policy ensures that marginal abatement costs are equal to marginal social costs of carbon at each point of time (compare Fuss et al. (2018)).

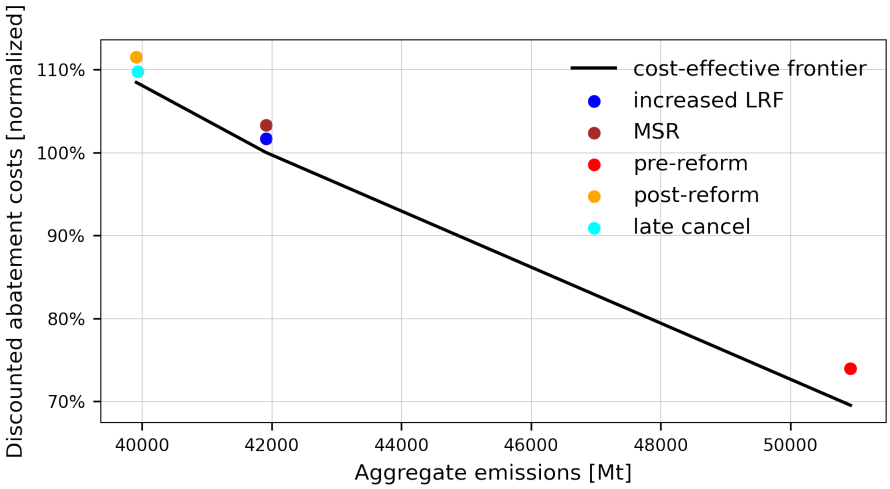

Figure 3.8.: Comparison of discounted abatement costs and emission levels in different scenarios

In general, all scenarios lie above the cost-effective frontier, i.e., firms cannot realize the cost-effective abatement path due to time-restricted availability of allowances. The time restriction on allowance availability is due to the non-borrowing constraint, the issue path of allowances and the temporal shifting of allowances through the MSR. Further, due to the underlying quadratic abatement cost function the curvature of the cost-effective frontier is convex. Higher abatement, leading to lower emissions, is disproportionately cost-intensive.

Comparing the pre-reform scenario (with unrestricted banking and no possibility to borrow) with a LRF of 1.74% and 2.2%, we see that increasing the LRF has a strong effect on the level of emissions, as also discussed in section 3.4.1. At the same time, increasing the LRF closes the gap between the cost-effective frontier and the discounted abatement costs. Increasing the LRF reduces the allowance supply - in particular in later periods - and hence diminishes the additional costs imposed by the non-borrowing constraint since fewer allowances can be borrowed from the future.

The MSR scenario adds a restriction on banking without changing the emission level (since the CM is not active in this scenario). It weakens cost effectiveness by shifting emissions into the future, antagonistic to firms' time preferences.

The CM invalidates about 2 billion allowances in 2023, cutting allowances by approximately 5% of allowances issued after 2017. Counterintuitively, this is not an instantaneous cancellation of allowances early on, but rather a reduction of future allowance supply since it eliminates reinjection from the MSR into the market in later periods (compare section 3.4.1). The cancellation changes little in the short-term abatement, impacting mainly the allowances available in later periods where the shadow costs of the non-borrowing constraint are rather low. Hence, the introduction of the CM slightly reduces the gap to the cost-effective frontier (+3.2%-points in the MSR scenario, +3%-points in the post-reform scenario). The discounted abatement costs increase due to the introduction of the CM according to the additional costs of tightening the emission budget.

To assess the cost effectiveness of the post-reform scenario, an alternative design of the CM is considered: In the late cancel scenario the cancellation is implemented by cutting the allowance supply from the long end, leaving allowances in the MSR unaffected, instead of instantaneously reducing the volume of the MSR in the post-reform scenario.[45] By construction, cost effectiveness in the late cancel scenario improves compared to the post-reform scenario.

As stated before, in the post-reform scenario the allowance supply is reduced by a shortening of the reinjection phase. In contrast, in the late cancel scenario the reinjection phase lasts longer, leading to more available allowances before 2050. Instead, the allowance supply is reduced from the very end and thus the last allowance is issued earlier than in the post-reform scenario. Hence, the alternative cancellation design enables firms to use the allowances more flexibly over time and to partly harmonize their abatement path with their time preferences.

Making the reinjection rate more flexible, e.g., by defining it as share of the previous years emission level or by increasing its value in early periods could further boost dynamic cost effectiveness, and may contribute to making the EU ETS more resilient towards demand shocks, which Perino and Willner (2016) identified as a drawback of the MSR.

Further, our theoretical evaluation of cost effectiveness neglects spillover effects. The price increase caused by the reform may trigger short-term investments into low-emission technologies which lower the costs for future abatement due to technological learning. Since firms do not internalize those spillover effects, the reform may induce benefits for cost effectiveness not accounted for in our model.

3.5. Conclusion

With the change of the linear reduction factor, the implementation of the market stability reserve and the introduction of the cancellation mechanism, the EU ETS changed fundamentally. This paper developed a discrete dynamic optimization model reflecting firms' optimal choice of abatement under the new regulation.

The results for the post-reform scenario including all three amendments show that about 5% of allowances issued from 2018 onwards are invalidated through a one-time cancellation in 2023. All remaining allowances in the MSR are reinjected into the market from 2029 to 2036. The assumed backstop costs of 150 EUR/t are reached in 2057. The level of the backstop costs solely scales the price

[45] The supply reduction is determined endogenously to prevent side effects on the optimization of individual firms.

path, but does not further impact the resulting quantities. Baseline emissions in absence of the EU ETS can only be estimated with significant uncertainty, but the assumption strongly drives model results. Higher baseline emissions increase emissions, abatement and prices and diminish the impact of the MSR and the CM.

Varying the interest rate has a similar effect. If firms have higher private interest rates, they choose to delay abatement and increase emissions in the short run, leading to a smaller MSR intake and cancellation volume. This extensive sensitivity analysis of the underlying parameter assumptions proved the robustness of the model results. While the choice of the parameter values influences the numeric results of the model, it does not impact the underlying modus operandi.

By decomposing the reform into its single amendments, we evaluate the economic impact and the dynamic cost effectiveness of these amendments individually. In the increased LRF scenario, we showed that with the higher reduction factor of 2.2% the total emission cap is reduced by over 9 billion allowances, and thus increases prices in the short and long run. We identify the change in the LRF as the main driver of change in the post-reform EU ETS. The MSR itself shifts emissions from the present to the future. This does not impact the overall emission cap, but adds a restriction on banking and thus deteriorates dynamic efficiency.

The CM changes little in the short run, but mainly reduces the available number of allowances in the long run by about 2 billion. Further, we show that an alternative cancellation of allowances from the long end increases the cost effectiveness within the model. Nevertheless, the MSR increases abatement costs for firms by shifting additional abatement to earlier periods and increasing emissions later on. The initial goal of the reform was to increase today's prices and thereby a signal to invest in low-carbon technology. We find that the intended effect of the introduction of the MSR with CM does not correspond to the design chosen by policy makers which impacts prices and emissions mostly in the long run. To increase the resilience of the EU ETS towards demand shocks and to avoid additional abatement costs stemming from the MSR, a more flexible reinjection rate should be considered by policy makers. Future research should take positive externalities, e.g., learning effects of abatement technologies or other spillover effects, into account which may enhance the advantages of the MSR.

The price increase in the real EU ETS in the aftermath of the reform cannot be explained by the model presented in the paper. This might be due to the fact that the assumptions of a competitive market with perfectly rational firms that optimize themselves under perfect foresight are violated in reality. Several market imperfections might exist that could lead to a deviation from those assumptions: Hedging requirements may for example lead to higher banking volumes independent of market prices. Therefore, the price increase in the aftermath of the current reform may be underestimated by our model. Further, it is possible that firms are myopic and only optimize themselves over the next few years instead of the long run. Thus, firms do not anticipate that allowances in the MSR will become available in the future but rather see the significant short-term cut in allowance supply induced by the reform. This leads to a stronger price increase due to the reform than in the perfect foresight case. Moreover, firms might face uncertainty regarding regulatory reforms. If firms perceive the recent reforms as a signal for increasing scarcity of allowances in the future, they purchase more allowances today, amplifying the price increase of the reform. We therefore argue that the price spike in 2018 is not solely driven by the new regulation but potentially intensified by regulatory uncertainty and bounded rationality, such as myopia and hedging requirements. Thus, further research should evaluate such market imperfections.

4. How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule

4.1. Introduction

Since 2005, the European Union Emissions Trading System (EU ETS) builds the foundation of European environmental policy. Aggregate emissions within the EU ETS are limited by the number of allowances supplied to the market. The cap is determined on a yearly basis and set to decline annually. Firms in the EU ETS can optimize themselves intertemporally by banking allowances for future use.

Due to low allowance prices in the market and hence a weak investment signal for low-carbon technology, policy makers reformed the EU ETS substantially between 2014 and 2018, including the backloading of allowances, the Market Stability Reserve (MSR) and a cancellation mechanism. As the aggregate private bank held by firms in the market determines the size of the MSR and the cancellation volumes, the allowance supply is partially endogenous in the reformed EU ETS.

In the aftermath of the reforms, prices in the EU ETS rose from 5 EUR/t in 2017 to over 24 EUR/t in 2019, while the aggregate private bank remained almost constant at around 1650 million allowances. Practitioners from the energy sector state that the reform fundamentals, namely the introduction of the MSR and the announcement of the cancellation mechanism, caused prices to spike (Wölfling and Germeshausen, 2019).

Theoretical models accurately depicting the new EU ETS regulation yet fail to attribute the large price increase in 2018 to the underlying reform fundamentals. Perino and Willner (2016) find that the MSR shifts allowances from the present to the future but is allowance preserving, i.e. the overall emission cap is not altered. They conclude that the MSR only affects prices if allowances become temporarily scarce. In this case, prices slightly increase in the short run but drop below their baseline level in the long run.

Bocklet et al. (2019) and Beck and Kruse-Andersen (2020) amend the work of Perino and Willner (2016) by including the cancellation mechanism into their models. Both papers find that the cancellation of allowances stored in the MSR increases the overall price level at all times but that the price increase is rather negligible in the short run.[46]

All three papers build on the seminal works of Rubin (1996) and Chevallier (2012) who established a model for intertemporal allowance trading. The right to emit is treated as a scarce, non-renewable resource. Prices of such a resource develop according to the Hotelling rule (Hotelling, 1931), given complete and perfectly competitive markets and rational firms that have perfect information and fully anticipate market and regulatory developments until the end of time. The Hotelling rule states that prices are determined by the discounted value of the expected backstop costs. The shortening of allowances caused by the reform shifts the price path upwards. Due to discounting, short-run prices only increase little while the main price effect of the reform plays out in the long run. Thus, those theoretical models fail to explain the price increase through the reform fundamentals. Krautkraemer (1998) challenges the assumptions of Hotelling models stating that governments intervene, firms have market power, are risk averse or shortsighted. Thus, theoretical Hotelling price paths are rarely visible in reality. Instead, the market depletion path can tilt towards the present or the future, prices may be volatile around a trend or even fully deviate from the Hotelling price path (Krautkraemer, 1998).

While there is no indication that the EU ETS lacks competition, literature and industry experts likewise stress the importance of myopia (e.g. Flachsland et al. (2019)) and hedging (e.g. Gallier et al. (2015), Cludius and Betz (2016) and (Kollenberg and Taschini, 2019)) - as a result of risk aversion - on market outcomes.

The role of either myopia or hedging requirements within the EU ETS has been previously researched by Willner (2018), Schopp and Neuhoff (2013), Tietjen et al. (2019) and Quemin and Trotignon (2019). Willner (2018) analyzes the impact of limited foresight in a two-period partial equilibrium model of the EU ETS. He finds that limited foresight leads to an underestimation of long-term scarcity. Consequently, prices are lower in period one and higher in period two than in the perfect foresight scenario and overall abatement costs increase. Given limited foresight, the introduction of the MSR leads to higher short-run prices and lower long-run prices than in the case with perfect foresight. A similar two-period partial equilibrium model is also set up in Schopp and Neuhoff (2013) where the allowance demand for hedging requirements is modeled in response to changes in expectation of fuel and power prices. They argue that if firms flexibly adjust their hedging needs, they can stabilize prices. Tietjen et al. (2019) understand hedging as a firm's response to uncertainty. Using a stochastic optimization model, they find that hedging leads to a U-shaped price curve in the EU ETS. They further evaluate how the introduction of the MSR changes the hedging decision of a firm. Quemin and Trotignon (2019) use a rolling-horizon

[46] Bocklet et al. (2019) further show that the main price effect stems from the increase of the linear reduction factor rather than the MSR and the cancellation mechanism.

model where firms are short-sighted and exhibit cognitive limitations in responding to governmental interventions. The model is calibrated to historic outcomes, choosing a planning horizon and interest rate that minimizes the difference between simulated results and historical data ex-post. They find that applying a low interest rate of only 3% and a planning horizon of 13 years historic data can be mimicked best.

This paper differs from the aforementioned approaches and assumptions in several aspects:

Myopia is incorporated through a rolling-horizon approach into a closed-form dynamic optimization model set up in Bocklet et al. (2019). Within the model, we depict the market and the recent reforms on a yearly resolution instead of deducing market results from a simplified two period model.

We evaluate the impact of the EU ETS reform on market outcomes by modelling an exogenous hedging share. Since firms hedge their future power sales, they may have limited potential to shift their portfolio to low-carbon production in the short run. It is therefore likely that their exogenous hedging requirement is substantially larger than an endogenously derived optimal bank.

As a further extension to previous work, we use stylized facts to determine the underlying fundamentals driving the market outcomes in the third trading period of the EU ETS. In particular, we compare pre- and post-reform model results with the observed market data. By analyzing model outcomes under myopia, hedging requirements and a combination of both, we shed light on the underlying fundamentals of the price increase caused by the reform.

The paper at hand adds three main contributions to the literature:

1. Implementing myopia into a discrete-time partial equilibrium model of the EU ETS where cancellation volumes are determined in a closed-form solution, we find that myopic firms emit more in the short run than under the cost-minimal abatement path. This market friction can be partly mitigated through the introduction of the MSR. At the same time, myopia leads to lower banking volumes and hence lower cancellation volumes. Thus, dropping the assumption of perfect foresight alters market outcomes in the dynamic setting of the reformed EU ETS.
2. By including firms with exogenous hedging requirements into the dynamic optimization model of the EU ETS, we show that hedging requirements drive cancellation volumes. Thus, prevalent theoretical models neglecting hedging requirements may underestimate the overall effect of the reform. Further, the restrictive allowance supply in the EU ETS along with the hedging requirements of firms may cause physical shortages in today's allowance market.

3. By comparing the model results with stylized facts of the EU ETS, we shed light on the underlying fundamentals driving market outcomes in the third trading period. Neither myopia nor hedging requirements on their own are able to fully depict the market outcomes. Only the combination of myopic behaviour, hedging requirements and the introduction of the reform is able to simultaneously explain low initial price levels, a steep price increase in the midst of the third trading period and a large private bank after the reform.

The remainder of this paper is organized as follows: In Section 4.2 we set up a partial equilibrium model of the EU ETS. Myopia and hedging requirements are integrated into the pre- and post-reform model. In Section 4.3 we show how myopia impacts model results in the reformed EU ETS. Analogously, in Section 4.4 we show how hedging requirements drive model results. In Section 4.5, we discuss if the reform can explain the market outcomes in the third trading period of the EU ETS given bounded rationality. Section 4.6 concludes.

4.2. A Hotelling Model of the EU ETS

Our partial equilibrium model of the EU ETS builds on the model presented in Chapter 3 by Bocklet et al. (2019) who use a discrete-time version of the model set up by Rubin (1996). In the following, we briefly outline the decision making of a representative firm in a perfectly competitive allowance market. Since the market consists of homogeneous firms, the market demand is derived by the aggregated choice of firms.

The base model assumes a representative firm which is deciding on emissions $e(t)$, banking $b(t)$ and net allowance sales $x(t)$ for all time periods $t = 0, 1, \dots, T$ under perfect foresight. Formally, the firm solves the cost minimization problem $\mathcal{M}$

$$\begin{aligned} \min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t} [\frac{c}{2}(u - e(t))^2 + p(t)x(t)] \\ \text{s.t.} \quad & b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = 1, 2, \dots, T \\ & b(t) \geq 0 \\ & x(t),\, e(t) \gtrless 0. \end{aligned} \tag{4.1}$$

The objective function consists of the discounted (interest rate r) costs for abatement and allowance trading. Following Perino and Willner (2016) and Bocklet et al. (2019), we assume a quadratic and convex abatement cost function with cost parameter c and baseline emissions u. The allowance price $p(t)$ is determined by the market and is hence exogenous in the firm's optimization problem. If allowance purchases exceed emissions, the constraint ensures that the excess allowances are stored in the private bank of the firm. According to regulation, borrowing is not allowed in the EU ETS. Thus, we require a positive bank. The optimality conditions for the firm are given by the Karush-Kuhn-Tucker (KKT) conditions, which are stated in the Appendix C.1.

To derive the market equilibrium conditions, the following sections introduce the pre-reform (Section 4.2.1) and post-reform (Section 4.2.2) market rules. In Section 4.2.3 we explain how we model myopic firms with a rolling horizon approach. Section 4.2.4 exhibits how the firm's decision problem changes in light of hedging requirements. The parameterization of the model is summarized in Section 4.2.5.

4.2.1. Pre-Reform Market

The pre-reform market is assumed to be the EU ETS 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.[47] In the following, the variables introduced above are used for aggregate levels, i.e. e and b are overall emissions and banking. Policy makers refer to the aggregated private bank b also as Total Number of Allowances in Circulation (TNAC).

In the pre-reform case with unrestricted banking, the supply of allowances is exogenously determined by the regulator.[48] The market equilibrium is determined by a price path such that the firm's optimality conditions hold and aggregated emissions over time do not exceed aggregated allowance supply, i.e. $\sum_{\tilde{t}=0}^{t} e(\tilde{t}) \leq \sum_{\tilde{t}=0}^{t} S(\tilde{t})$ for all $t = 0, 1, \ldots, T$.

From the market equilibrium conditions and the KKT conditions, we can derive an amended Hotelling price rule

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1} \frac{\mu_b(t)}{p(t)}. \tag{4.2}$$

Hence, the market price rises with the interest rate as long as the aggregated private bank is greater than zero.[49] If the bank drops to zero, prices rise at a lower rate.

[47] Since the EU ETS has been reformed in 2015 and 2018, the pre-reform case serves as a counterfactual after the reform is introduced.

[48] We amend the allowance supply by the expected number of unallocated allowances equally distributed over the years 2013-2020.

[49] We assign the dual multiplier $\mu_b(t)$ to the banking flow constraint in the firm's optimization problem.

4.2.2. Post-Reform Market

In the post-reform market the reforms on backloading of allowances, the MSR and the cancellation mechanism are included in the model.[50]

Backloading refers to the decision made by policy makers in 2014 to postpone the auctioning of 900 million allowances. It is implemented in the post-reform model as a reduction of the auction volumes in 2014, 2015 and 2016. In line with regulation (c.f. European Parliament and the Council of the European Union (2015)), the backloaded allowances are inserted into the MSR in 2019 and 2020 together with allowances that remain unallocated in the third trading period.

The MSR was established by the European Commission in 2015, became operational in 2019 and serves as a public bank of allowances that shifts the allowance supply partly to the future while keeping the total number of allowances constant (European Parliament and the Council of the European Union, 2015). In 2018, the EU introduced a cancellation mechanism that will become operational in 2023. If the cancellation mechanism is activated, it renders a share of allowances stored in the MSR invalid (European Parliament and the Council of the European Union, 2018).

With the introduction of the MSR and the cancellation mechanism, the allowance supply is no longer exogenously determined. If the TNAC exceeds a certain threshold ℓ_{up}, a share ($\gamma(t)$) of allowances is withheld from the auction and put into the MSR. If the TNAC falls below the threshold ℓ_{low}, R allowances are reinjected from the MSR into the auction. With $a(t)$ being the exogenous linear reduction factor, the partly endogenous allowance supply is given by

$$S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct} - Intake(t) + Reinjection(t). \tag{4.3}$$

The intake to the MSR and the reinjection from the MSR to the market are defined as

$$Intake(t) = \begin{cases} \gamma(t) \cdot TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{4.4}$$

and

[50] In order to show the effect of the reform, we model the post-reform scenario from 2013 onwards. The post-reform scenario before the reforms thereby serves as a counterfactual which postulates that the market participants are already aware of the upcoming policy changes in 2013.

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else.} \end{cases} \quad (4.5)$$

Hence, the volume of allowances in the MSR is given as

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t). \quad (4.6)$$

If the MSR exceeds the auction volume of the previous year, allowances in the MSR are invalidated for future use, such that

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \quad (4.7)$$

The accurate modelling of the MSR and cancellation mechanism within our partial equilibrium model allows for a closed-form solution of MSR and cancellation volumes.

4.2.3. The Model under Myopia

In economic theory, perfect foresight postulates the assumption that the decision maker is fully informed about the exogenous environment at every point in time. Thereby, firms optimize themselves until the end of time, markets clear at all states and prices follow expectations (Bray, 2018). In reality, however, firms are either incapable or unwilling to consider the long-term future (Edenhofer et al., 2017) or regulatory uncertainty regarding the long-term future forces firms to neglect it. Thus, it is likely that firms are myopic, i.e. decide under a limited planning horizon. As time goes by, firms update their decisions in a rolling horizon model.

In this section, we therefore deviate from the assumption of perfect foresight and assume that firms are prone to myopia. For a planning horizon of H years the decision problem $\mathcal{M}(\tau, H)$ of the myopic firm with start year τ can be formulated as

$$\begin{aligned} \min \quad & \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\ & s.t.\ b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = \tau, \tau+1, \ldots, \tau+H \\ & b(t) \geq 0 \\ & x(t),\ e(t) \gtrless 0. \end{aligned} \tag{4.8}$$

In the start year τ the myopic firm decides on emissions, banking and allowance trade only for the next H years. The firm disregards any information about the future after this planning horizon.[51] Further, the firm is able to update its decisions as time passes and future unveils. We implement this updating procedure with a rolling horizon approach:

Algorithm: Rolling horizon of the myopic firm

for $\tau = 0, 1, \ldots, T$ **do**
  Solve $\mathcal{M}(\tau, H)$;
  Fix $e(\tau)$, $x(\tau)$, $b(\tau)$;
end

Accordingly, the firm optimizes itself from the current year τ until $\tau + H$ and implements the decision for the current year. In the next year, the firm's planning horizon is extended and the firm is able to plan for the next period, taking into account the implemented decisions from previous periods. During this next planning phase, all future decisions can be revised in order to process new information. Hence, the Hotelling price rule holds in the planning process but may not be visible ex-post.

4.2.4. The Model with Hedging Requirements

In this section, we deviate from the assumption of perfectly rational firms and assume that firms are risk averse. Power producers, and thereby the largest group of emitters in the EU ETS, hedge against allowance price risk based on the quantity of power sold forward (Doege et al. (2009) and Cludius and Betz (2016)). The precise hedging strategy strongly depends on the flexibility of the

[51] In the extreme case that firms only have a planning horizon of one year, the dynamic optimization problem becomes static and $b(t) = 0$ for all $t = 1, \ldots, T$.

portfolio and thus differs among companies and industries (Schopp and Neuhoff, 2013). We assume that the homogeneous firms in the model have the same hedging requirements and hedge themselves through a buy-and-bank strategy, i.e. by holding allowances in their private bank to cover a certain share of their planned emissions for the upcoming years.

The non-negativity constraint for banking from the cost minimization problem $\mathcal{M}$ (Equation 3.2) needs to be adjusted in order to take the hedging requirements into account, so that

$$b(t) \geq \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t}-t) \cdot e(\tilde{t}), \tag{4.9}$$

where $hedgeshare(\tilde{t}-t)$ is an exogenous parameter defined by the firm that expresses how many allowances need to be banked in period t for emissions in the future period $\tilde{t}$. This adjustment of the constraint changes the corresponding Lagrangian and equilibrium conditions which are stated in C.1. We receive the amended Hotelling rule (Equation 4.2) with the dual variable $\mu_b(t)$ for the hedging constraint (Equation 4.9). Accordingly, the price increases with the interest rate if the firms bank more than their hedging requirements. If the hedging requirement becomes binding, prices are allowed to deviate from the Hotelling price rule.

4.2.5. Parameterization

The above models are implemented as mixed integer models in GAMS and solved with CPLEX. To do so, the model is parameterized to depict the actual regulatory setting of the EU ETS.

The regulatory parameters of the exogenous and endogenous supply rules are taken from the EU regulation. The initial supply in 2010 is 2199 million allowances and set to decline with a linear reduction factor of 1.74% until 2020 and 2.2% afterwards (European Parliament and the Council of the European Union, 2018).[52] The auction share remains constant over time at 57%. The TNAC at the beginning of the third trading period is set to 2109 million allowances (European Commission, 2019c). For the post-reform model, the upper and lower thresholds of the MSR are set to $\ell_{up} = 833$ and $\ell_{low} = 400$, respectively. Further, $\gamma(t)$, the share of the TNAC which is inserted into the MSR is 24% until 2023 and 12% afterwards. If the TNAC falls below the lower threshold, tranches of $R = 100$ million allowances are reinjected to the market (European Parliament and the Council of the European Union, 2015). The MSR is initially endowed with 900 million backloaded allowances. We further assume that

[52] In order to decouple the effect of the MSR and the cancellation mechanism from the effect of the increased linear reduction factor, we also adjust the linear reduction factor in the pre-reform scenario.

a total of 600 million unallocated allowances are inserted into the MSR in 2020 (European Commission, 2015).

Since EU ETS regulation beyond 2030 is not decided on yet, the results depicted in Section 4.3 and Section 4.4 focus on the third and fourth trading period, showing results from 2013 until 2030. However, it is indisputable that the EU ETS will continue beyond the fourth trading period.[53] Thus the model is run until 2057 when the EU ETS is assumed to reach zero emissions.[54]

In addition to the regulatory parameter values described, further parameter assumptions are needed: The level of baseline emissions is assumed to be exogenously given at $u = 2130$ million tonnes CO_2 equivalent (CO_2e) and held constant over time as e.g. in Perino and Willner (2016). We follow Bocklet et al. (2019) and determine the cost parameter c through the price of a backstop technology with backstop costs $BC = 150$ EUR/t CO_2e such that $c = \frac{BC}{u}$. Further, all costs are discounted at a yearly interest rate of $r = 8\%$.[55]

Since there is no consensus on the level of myopia and the hedging requirements of firms, we depict various scenario results covering a wide range of parameter assumptions. The planning horizon of firms widely differs among industries, size and ownership structure. In Section 4.3, we show the results for planning horizons H of 3, 5 and 10 years and compare them to the results under perfect foresight. The wide range of planning horizons depicts the discrepancy found in the literature: Stonehouse and Pemberton (2002) find that two thirds of the small and medium sized manufacturing firms have a planning horizon of 1-3 years. Edenhofer et al. (2017) suggest that power producers have planning horizons of 5-6 years. Souder et al. (2016) research publicly traded manufacturing firms and find an average planning horizon of 12 years.

Comparably, the parameterization of the hedging share is meant to reflect a broad range of potential hedging schedules. A study by Eurelectric (2009) evaluates the hedging requirements of forward power sales from large power producers in Europe. It suggests that at least 60% of power sales are hedged one year ahead, 30% two years ahead and 10% three years ahead.[56] While power generators tend to buy derivatives to hedge the inputs for their power sales, non-regulated entities such as financial investors buy the respective physical allowances on the spot market (Cludius and Betz, 2016). They hereby act as counterparties for the power generators so that the allowance futures of the forward power sales are

[53] In light of the 'European Green Deal' recently announced by the European Commission, it seems likely that the number of issued allowances will decline even faster. In that case, the last allowance would be issued earlier and the backstop costs would be hit earlier.

[54] In the Hotelling model the point in time where the model reaches zero emissions falls together with the point in time where marginal abatement costs equal the backstop costs.

[55] An extensive sensitivity analysis of those parameter assumptions can be found in Bocklet et al. (2019).

[56] This is in accordance with the publication of one of Europe's biggest power producers who stated in 2019 that at least 60% of their power sales were hedged until 2022 (RWE AG, 2019).

fully hedged through a buy-and-bank strategy. We assume that firms are not able to deviate from their exogenous hedging schedules.

	$t+1$	$t+2$	$t+3$
0%	0%	0%	0%
40%	40%	20%	6.67%
60%	60%	30%	10%
80%	80%	40%	13.33%

Table 4.1.: Exogenous hedging schedules

We depict a wide range of possible hedging requirements by scaling the hedging schedule above described proportionally.[57] The hedging shares for the different hedging schedules are given in Table 4.1.

4.3. Model Results under Myopia

As stated in Section 4.2.3, it is often assumed that firms have a limited planning horizon. Therefore, the aim of this section is to understand how myopia changes the model results of the EU ETS in the pre- and post-reform scenarios.

Myopic firms have a limited planning horizon H. Hence, they neglect all information (e.g. allowance demand and regulatory rules) beyond this planning horizon $t + H$. As time goes by, the future unfolds and firms update their decisions based on the revelations.

Figure 4.1 compares the results (prices, emissions, TNAC and MSR) of the pre- and post-reform model for different degrees of myopia (planning horizon of 3, 5 and 10 years as well as perfect foresight).

Under perfect foresight, emission levels in the short and medium run are strictly smaller in the post-reform case. In accordance with the firm's equilibrium constraint (allowance price equals marginal abatement cost), price levels are strictly larger in the post-reform case. However, the overall price effect of the reform is small, in particular in the short run, since the cancellation of allowances stored in the MSR leads to a supply reduction from the long end. This finding is in line with the findings of Bocklet et al. (2019) and Beck and Kruse-Andersen (2020).

Once the assumption of perfect foresight is dropped, the divergence between pre- and post-reform model results becomes more noticeable.

In the pre-reform case, myopia leads to considerably lower short-run prices than under perfect foresight. The shorter the planning horizon H of a firm, the lower short-run prices. Consequently, emissions of myopic firms are high

[57] We only implement hedging requirements on the share of auctioned allowances and thereby assume that free allowance allocation serves as an implicit hedge.

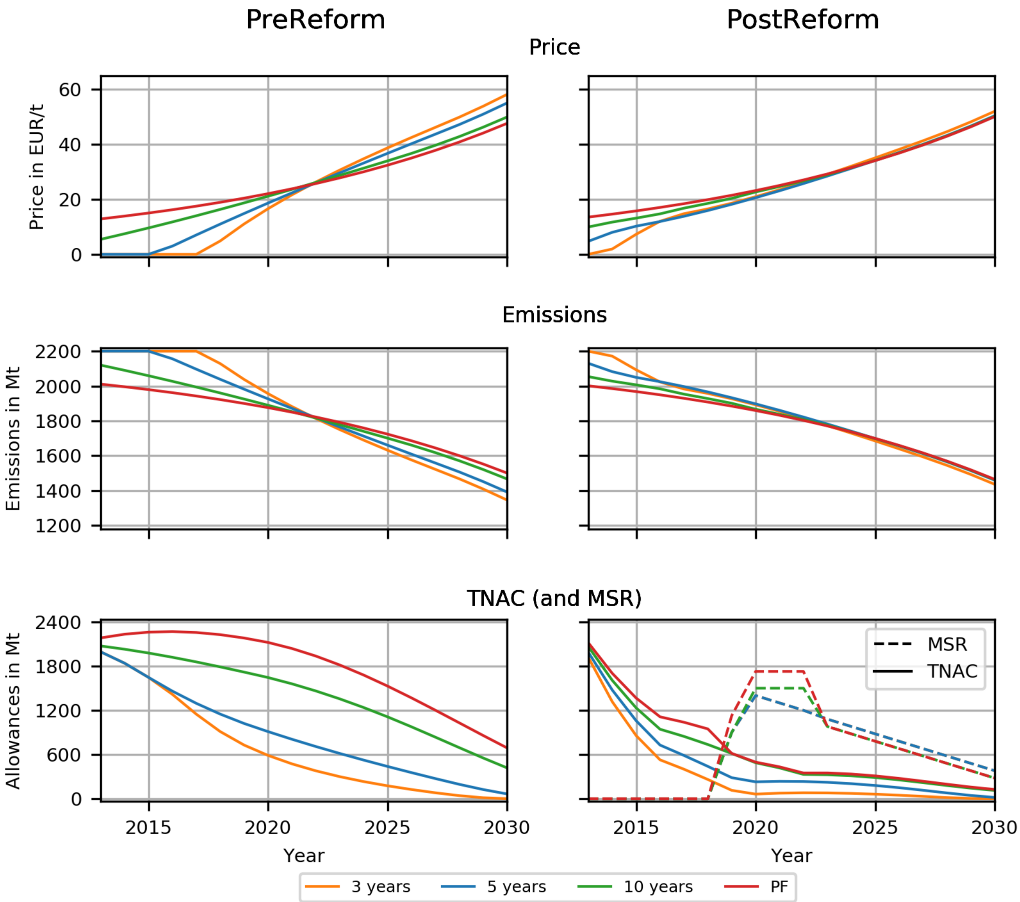

Figure 4.1.: Allowance prices, emissions, TNAC and MSR for the pre- and post-reform scenario with different planning horizons

and abatement efforts are low in the short run.[58] Due to the large "surplus" of allowances early on, short planning horizons even lead to prices of zero. This implies no abatement efforts since baseline emissions can be completely covered by the initial TNAC and the respective yearly supply.

These large emission levels early on as well as the small TNAC kept by myopic firms induce long-run scarcity. Thereby, emission levels in the long run lie below those of firms with perfect foresight. Correspondingly, by 2030 prices under myopia are higher than prices under perfect foresight. Since myopic firms update their decisions as soon as future scarcity unveils, the shorter the planning horizon of firms, the steeper the corresponding price increase.

[58] Following the common assumption that environmental pollution exhibits convex damage curves, i.e. early emissions cause more damage than later ones (Rubin, 1996), myopia increases environmental damage cost.

While myopia changes the banking behaviour of firms, the banking decision determines the size of the MSR and thereby the overall allowance cap. Thus, given that firms are myopic, the EU ETS reform considerably alters the market outcome, as shown in the post-reform scenario.

Under myopia the initial allowance price level is below the price level in the case of perfect foresight. As in the pre-reform scenario, this is due to the fact that myopic firms disregard the future scarcity of allowances and hence emit more in the short run, resulting in a smaller TNAC. Comparable to the pre-reform scenario, the smaller the planning horizon H, the lower the prices in the short run. However, since the allowance supply is eventually delayed through the MSR intake, prices are expected to increase. While this supply reduction is priced-in under perfect foresight, myopic firms do not foresee the resulting price increase caused by this supply reduction, and thus prices increase at a rate above the interest once firms update their decisions. This price increase in light of the MSR intake is thus steeper than under perfect foresight. In order to account for this short-term supply shortage, myopic firms correct their banking decision upwards as the future unfolds.

As firms hold an overall smaller TNAC in the short run, long-run scarcity increases for shorter planning horizons. This causes the firms to update their decisions more strongly to match the decreasing allowance supply. Hence, firms correct their emission levels downwards and their banking levels upwards, overall causing prices to deviate upwards from the original Hotelling path. Due to the rolling horizon model and the updating of firms' decisions, the Hotelling price rule does not hold ex-post, despite its relevance in the planning process of the firm ex-ante. Since prices increase steeper than predicted by the Hotelling price rule, the price level in 2030 is higher under myopia than under perfect foresight.

In order to evaluate the effect of the reform, we compare the results of the pre- and the post-reform model under myopia. Two main aspects are worthwhile to notice:

First, initial prices in the post-reform model exceed those in the pre-reform model. Because of backloaded and unallocated allowances, the overall allowance supply in early years is significantly smaller in the post-reform than in the pre-reform scenario.[59] This finding also holds for perfect foresight, but the effect gets stronger under myopia.

Second, in the long run the divergence between prices under myopia and perfect foresight is substantially smaller in the post-reform than in the pre-reform setting. Thus, the reform mitigates the market frictions created by myopia.[60] The reason for this lies in the intertemporal shift of the allowance supply induced

[59] 900 million allowances are backloaded and 600 million allowances remain unallocated. Thus, 1500 million allowances are stored in the MSR instead of being auctioned.

[60] Despite the difference in the modelling approach, our findings thereby support the intuition shown in Willner (2018) who argues that the MSR decreases the additional costs imposed by myopia and moves the market closer to the minimum cost outcome under perfect foresight.

by the MSR. If firms are myopic, e.g. $H = 5$, they do not account for the higher price level caused by the MSR intake. Hereby, firms overestimate the availability of allowances in future markets and underestimate market prices. The smaller the planning horizon, the smaller the TNAC. This is also found by Quemin and Trotignon (2019). A small TNAC leads to low MSR intake and (if any) low cancellation volume. Thus, under myopia, the reform reduces the overall allowances supply only little. Contrary, if firms have long planning horizons or even perfect foresight, they bank in order to follow their optimal abatement path. Hence the MSR intake is larger and more allowances are canceled, reducing the overall allowance supply.

Against first intuition, the overall supply reduction induced by the reform is substantially higher under perfect foresight than under myopia. If firms are extremely myopic, the MSR mechanism will not be triggered and no allowances will be canceled at all. Yet, despite larger cancellation volumes under perfect foresight, the total discounted abatement costs are always smaller.

4.4. Model Results with Hedging Requirements

As discussed in Section 4.2.4, firms may be risk averse and hence follow hedging schedules to mitigate their allowance price risk. In order to understand how hedging requirements of firms drive the model results of the EU ETS, we analyze in this section the impact of different hedging shares in the pre- and post-reform market.

Figure 4.2 shows the model results under perfect foresight for the different hedging schedules given in Table 4.1. In the pre-reform case, the impact of hedging requirements is rather small. For all considered hedging schedules, prices follow the Hotelling rule throughout the time span considered. Because the short-run supply of allowances is rather high in the pre-reform case, firms hold a relatively large TNAC even without hedging requirements, e.g. the TNAC falls below 1500 Mt of allowances only after 2027, whereas the hedging volume starts to decline from 1500 Mt in 2013 even in the high 80% case. Thus, in the pre-reform case, even for large hedging shares the hedging constraints are not binding during the considered time period but only bind after 2035. As hedging constraints become binding earlier for high hedging requirements, the price level increases slightly with the hedging share, leading to slightly lower emissions and a higher TNAC. The price level of the 80% case in 2030, for example, is only 6% above the scenario without hedging requirements, leading to fewer aggregated emissions of 350 Mt until 2030. Given this hedging schedule, the corresponding TNAC is about 350 million allowances larger than without hedging requirements.

In contrast, in the post-reform case hedging requirements have a major impact on the price development. Without hedging requirements and with hedging shares below 40% the Hotelling price path is still feasible throughout the time

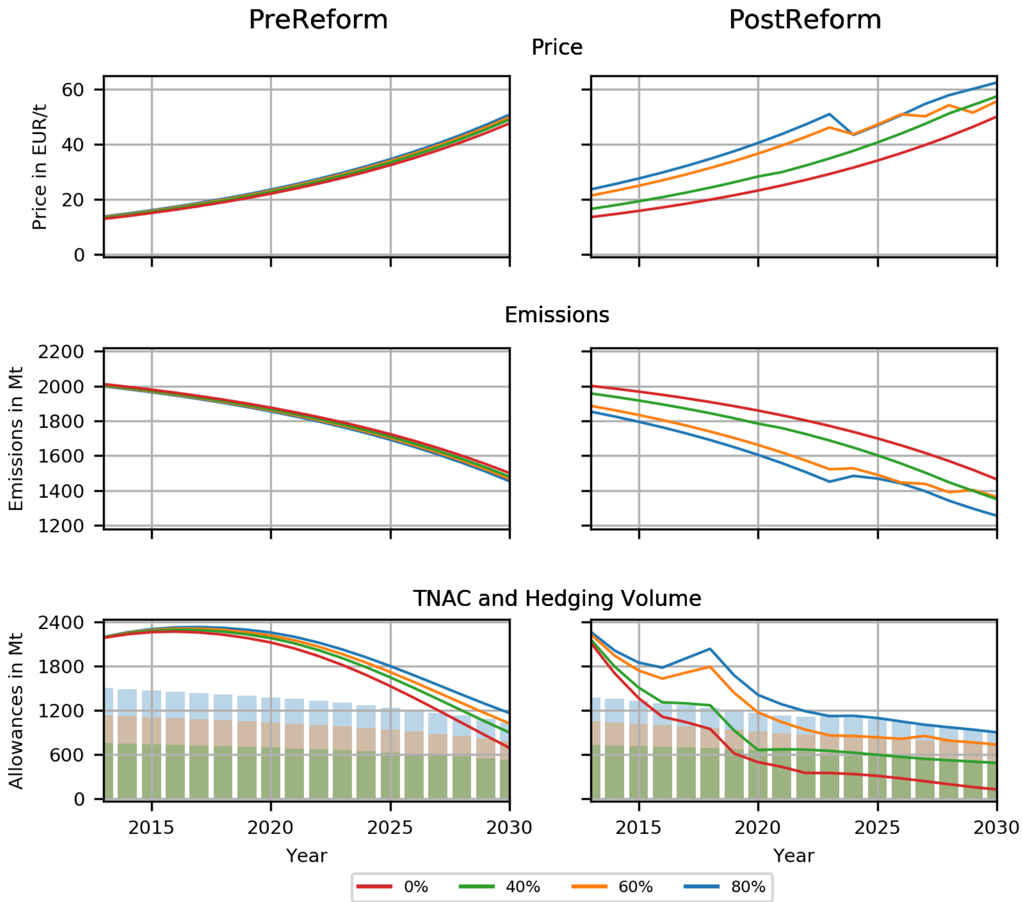

Figure 4.2.: Allowance prices, emissions, TNAC and hedging volumes for the pre- and post-reform scenario with different hedging schedules

span considered. However, with larger hedging shares (e.g. in the 60% and 80% case), the Hotelling price path is only feasible for certain periods of time (e.g. until 2023). The price path is corrected downwards when the hedging constraint binds (e.g. between 2023 and 2024 by 1% and by 12%, respectively).

As the short-run supply of allowances is smaller in the post-reform case (due to backloading and the MSR), the TNAC decreases sharply without hedging requirements, enabling relatively high emissions and low prices. As hedging requirements are introduced, the TNAC is obliged to lie above the required hedging volume (which is increasing with the hedging share and decreasing with future emissions). Emissions therefore have to be reduced in the short term in order to bank the ”excess” allowances for hedging requirements for future emissions. This drives down emissions while simultaneously driving up prices as they have to be equal to marginal abatement costs.

Additionally, hedging requirements lead to a supply shortage of allowances in the short run. As allowances are needed not only for compliance but also for hedging, this scarcity of allowances drives prices up. The price dumps shown in Figure 4.2 (e.g. from 2023 to 2024 under the 60% hedging schedule) depict the point in time when hedging requirements become binding but the aggregated supply up to this point does not suffice for a higher emission level when simultaneously fulfilling the hedging requirements. One can conclude that a supply shortage occurs in the short run which is resolved once the annual allowance supply increases due to the reduced intake rate of the MSR.

The model allows for such downward corrections of prices as the Hotelling price rule (Equation 3.4) is only applied if the TNAC is strictly greater than the required hedging volume. A smoothing of the price path to follow the Hotelling rule is not possible because of two effects: on the one hand, it is not feasible for equilibrium prices to be on a lower level before the price dump, as this would require more emissions and hence a larger hedging volume and a higher allowance demand, which is not met by the allowance supply in that time.[61] On the other hand, it is not feasible for the equilibrium price path to move to a higher level after the price dump. This would require more abatement efforts and hence lead to unused allowances. Consequently, neither a lower equilibrium price level before the price dump nor a higher equilibrium price level after the price dump would lead to an efficient abatement path. Hence, given the restrictive allowance supply, a price dump is inevitable for larger hedging requirements.

The higher the hedging requirement, the earlier the supply shortage happens, resulting in more abatement efforts before and less abatement efforts after the supply bottleneck. Before the price dump in 2024 for example, the price level in the 80% hedging scenario is 71% higher than in the scenario without hedging requirements. This price difference reduces to 28% in 2030. Until 2030, a hedging share of 80% leads to 3600 Mt C02e fewer emissions than without hedging requirements. The correspondingly larger TNAC triggers an additional cancellation of 2600 million allowances.

To understand the effect of the EU ETS reform under hedging requirements, we compare the pre- and post-reform model results. The EU ETS reform increases overall prices in the third and fourth trading period.[62] Without hedging requirements the reform increases prices only little (cf. Beck and Kruse-Andersen (2020) and Bocklet et al. (2019)). However, the larger the hedging share, the larger the price effect of the reform. While hedging requirements call for a TNAC of a certain size, the MSR reduces the number of allowances available for banking. Thus, the hedging constraint becomes binding earlier in the post-reform setting,

[61] This shortage is due to the short-run supply shortage induced by the reform and the restrictive allowances supply. If the regulator would issue all allowances at the start of the EU ETS instead of issuing allowances on a yearly basis, firms could follow their optimal abatement path, leading to a cost-efficient market outcome as depicted by the original Hotelling model.

[62] A long term price effect of hedging requirements or the reform does not exist, as finally backstop costs have to be met in every Hotelling model.

increasing prices. Additionally, the MSR and cancellation volumes also increase with the hedging shares as the hedging requirements increase the TNAC. This leads to a shortage of allowances in the post-reform case with large hedging requirements, amplifying the price effect of the reform. This is in line with Tietjen et al. (2019) who suggest that neglecting hedging requirements may have led to a underestimation of cancellation volumes.

Since the Hotelling price rule only holds as long as the TNAC is larger than the respective hedging requirements, the physical shortage of allowances in the short-run leads to an elevated price level followed by a downward correction of the Hotelling price path.

4.5. Explaining the Market Outcomes of the Third Trading Period

So far, theoretical models fail to give fundamental explanations of the market outcomes in the third trading period and in particular the allowance price increase in the aftermath of the EU ETS reform. As shown in Bocklet et al. (2019), the MSR and cancellation mechanism cause a price increase mainly in the long run. Hence, in models under perfect foresight the price increase in the short run is only small since prices are discounted based on the Hotelling rule.

In reality, allowance prices in the EU ETS remained at a low level at the beginning of the third trading period and rose significantly in the aftermath of the reform. Despite this price spike, the TNAC remained roughly at the same level.

In this section, we replicate those stylized facts of the third trading period in order to unravel the underlying drivers of the EU ETS market outcomes. Using our theoretical Hotelling model with myopia and hedging requirements, we replicate in particular the following market outcomes of the EU ETS (European Commission, 2019c):

- At the beginning of the third trading period and before the reform, prices remained at a low average price level of 5 EUR/t in 2013.
- Annual allowance prices rose to over 24 EUR/t in 2019.
- The TNAC fell from around 2100 million allowances in 2013 to around 1650 million allowances in 2016, where it roughly remained since.

In order to compare the model results with the real market outcomes, the prices of the pre-reform model in 2013 serve as benchmark for the initial price level. The difference between the pre-reform price in 2013 and the post-reform price in 2019 is compared to the price increase observed in the third trading period.[63] The private bank in the post-reform scenario is compared to the real TNAC in 2018.

4.5.1. Explaining Market Outcomes through Myopia

We first evaluate if the market outcomes can be explained through the reform fundamentals given that firms are myopic.

As discussed in Section 4.3, the more myopic a firm is, the lower the initial price level in the market. We find that a planning horizon of 10 years is able to replicate the observed price level in the beginning of the third trading period best (compare Figure 4.3).

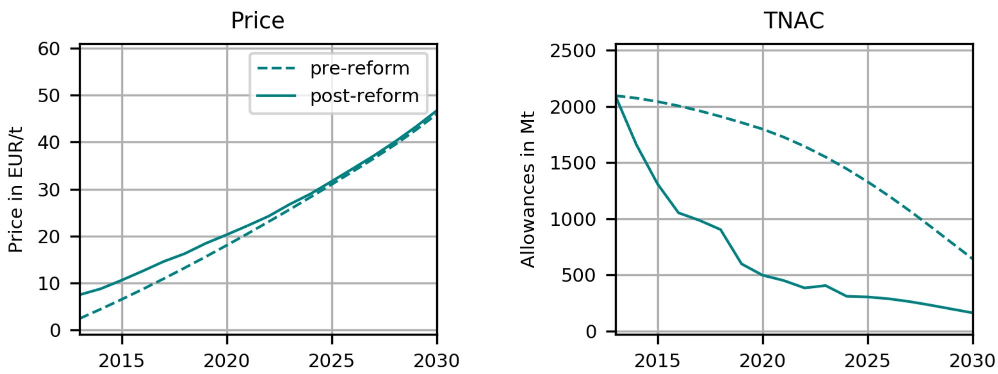

Figure 4.3.: Impact of the reform on market outcomes with a planning horizon of 10 years

The respective scenario results show a price increase of around 16 EUR/t and thus a similar size than the absolute price increase of 19 EUR/t observed in the market. A shorter planning horizon captures the price increase even better, but at the same time decreases the initial price level below the price level observed in the beginning of the trading period. Note that given myopia, the reform itself impacts prices only little but the main part of the price increase is caused by the updating of the rolling horizon approach. Thus, prices would have increased in almost similar magnitude even without the reform.

A planning horizon of 10 years further leads to a private bank of only 900 million allowances in the post-reform scenario in 2018, only half the size of the real TNAC. Longer planning horizons - or even perfect foresight - replicate the real TNAC better. However, a large private bank comes at the expense of higher initial prices and a smaller price increase.

[63] The market outcomes in the EU ETS are driven by firms' expectations. Since it is not clear at what point of time firms acknowledge the new regulatory setting, we refrain from depicting a precise transition path from the pre- to the post-reform scenario. The post-reform scenario before firms adapt to the reform and the pre-reform scenario after the reform has been acknowledged serve as counterfactuals, respectively.

Since myopia reduces the initial price level and the private bank while increasing the price effect induced by the reform, the stylized facts can not be met simultaneously through a variation of the planning horizon.

We conclude that if firms are myopic, the price increase observed in the market has not been caused by the reform fundamentals but mainly by the updating of firm's decision in order to meet the reduced allowance supply. Since myopia lacks explanatory power when it comes to the large bank held by firms in the market, we reason that myopia was arguably not the only fundamental driver of market outcomes in the third trading period.

4.5.2. Explaining Market Outcomes through Hedging Requirements

We now turn to the alternative explanation, namely that given hedging requirements, the EU ETS reform leads to a price increase and a TNAC of a considerable size. As analyzed in Section 4.4, the larger the hedging requirements, the larger the price effects induced by the reform. However, large hedging schedules also imply large initial prices levels and thus constitute a mismatch to the market outcomes observed in the EU ETS.

Nonetheless, we find that if firms apply a hedging schedule of 60% the stylized facts observed in the market can be replicated best (compare Figure 4.4).

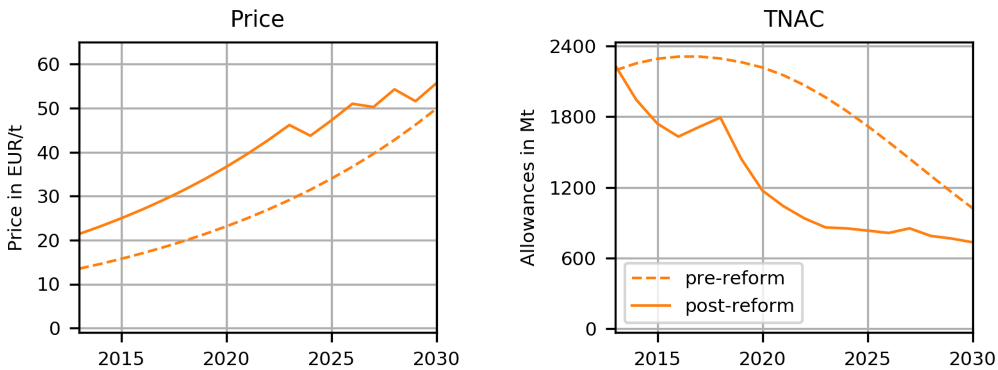

Figure 4.4.: Impact of the reform on market outcomes with a hedging schedule of 60%

If firms follow this exogenous hedging schedule, prices increase by over 18 EUR/t between 2013 and 2019. The difference between the pre-reform price path and the post-reform price path grows over time. Hence, the later firms acknowledge the reform, the steeper the price increase visible in the market.

Besides the absolute price increase, the 60% hedging schedule also replicates the banking behavior of firms in the market well. In order to account for the supply shortage induced by the MSR intake, firms keep an average private bank of around 1700 million allowances between 2017 and 2019, comparable to the magnitude of the TNAC observed in the market.

Thus, two stylized facts, the absolute price increase and the level of the TNAC, can be replicated by incorporating hedging into the model.

Still, none of the hedging schedules are able to depict the absolute price level in particular in the beginning of the third trading period since perfect foresight causes firms to abate already in the short run.

We conclude that given hedging requirements, the model performs well in attributing the price increase to the EU ETS reform. While hedging requirements are also able to explain the large private bank held by firms in the market, they lack explanatory power when it comes to replicating the absolute price level in the beginning of the third trading period. Thus, hedging requirements on their own cannot fully explain the impact of the reform on market outcomes in the EU ETS.

4.5.3. Explaining Market Outcomes Through a Combination of Myopia and Hedging Requirements

In the previous sections, we find that neither myopia nor hedging requirements are able to fully explain the impact of the reform on stylized EU ETS market outcomes. Thus, we examine whether a combination of both forms of bounded rationality is able to capture the market outcomes of the EU ETS.[64]

When applying a planning horizon of 10 years along with a hedging schedules of 50%, i.e. if firms hedge 50% of their allowances one year ahead, 25% two years ahead and 8% three years ahead, the model results match the stylized facts (compare Figure 4.5):

The initial price level in the pre-reform scenario lies at 4 EUR/t and therefore only slightly below the price level in the beginning of the third trading period. Due to the reform, prices rise to 26 EUR/t in 2019 in the post-reform scenario, closely resembling the price increase visible in the market. The real world TNAC until 2014 matches the private bank modeled in the pre-reform scenario and closely resembles the post-reform private bank of around 1630 million allowances in 2018.

The simple comparison of the model results with the stylized facts in Figure 4.5 suggests that firms in the market started taking notice of the policy changes already before the last reform took place in 2018 by adjusting their decisions in expectation of the post-reform regulation. The price increase observed in the

[64]While hedging requirements and myopia might seem conflicting concepts at first, it is likely that even though firms have a limited planning horizon, they mitigate price risk within the respective planning horizon. Thus, myopia and hedging requirements can be combined as long as the planning horizon exceeds the time span of the hedging schedule.

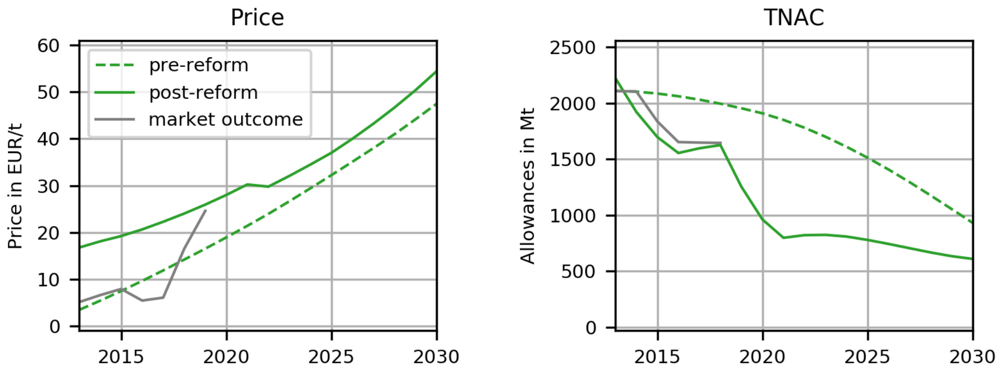

Figure 4.5.: Impact of the reform on market outcomes with a planning horizon of 10 years and a hedging schedule of 50%

midst of third trading period thereby reflects the transition from the pre-reform to the post-reform market.

In conclusion, we find that a theoretical model of the EU ETS is indeed able to attribute the price increase to the reform fundamentals if myopia and hedging requirements are both taken into account.

4.6. Conclusion

In this chapter, we use a discrete-time partial equilibrium model to analyze the impact of the EU ETS reform on allowance prices. We contribute to the existing literature by finding that theoretical models of the EU ETS need to take bounded rationality into account when they aim to explain the sudden price increase of the recent reforms in the midst of the third trading period. We show that even though the Hotelling price rule is ex-ante applied in a firm's planning phase, it is not necessarily visible ex-post in a setup that considers myopia or hedging requirements. In line with the suggestions of Krautkraemer (1998), we show that prices deviate ex-post from the Hotelling price path if regulatory interventions and bounded rationality, such as myopia and hedging, are considered.

While myopia and hedging requirements do not have a major impact on the pre-reform model results, they strongly drive results once the EU ETS reform (i.e. backloading, the MSR and the cancellation mechanism) is introduced:

First, if firms are myopic, they neglect future scarcity of allowances by emitting more in the short run than under the cost-minimal abatement path. This friction is mitigated by the introduction of the MSR which counteracts the firm's time preferences. The effect of the cancellation mechanism diminishes under myopia, as a short planning horizon implies a small private bank and thus low cancellation volumes.

Second, hedging requirements reinforce the impact of the reform on model results. In particular, cancellation volumes increase with hedging requirements. Thus, if hedging requirements are considered, the overall effect of the reform is larger than depicted by the prevalent theoretical models. Further, the restrictive allowance supply in the EU ETS along with binding hedging requirements of firms lead to physical shortages in the market. Thereby prices might even decrease when the binding hedging constraint suspends the Hotelling price rule.

Further, we find that under myopia as well as hedging requirements prices in the EU ETS increase in the short run. While myopic behavior on its own fails to explain the large private bank held by firms in the market, hedging requirements by themselves cannot explain the low price level in the beginning of the third trading period. If both forms of bounded rationality are combined, the initial price level, the price increase and the large TNAC can be simultaneously replicated within a theoretical Hotelling model. We deduce that a combination of myopia and hedging requirements provoked the reform to fundamentally increase prices and might thus be the missing piece to the puzzle.

In this chapter, we model market frictions caused by myopia and hedging requirements. Thereby, other forms of bounded rationality and other market frictions, such as asymmetric information or incomplete markets, are not considered within our model. Further, the model is simplified by assuming that risk averse firms stick to exogenous hedging schedules. We thus neglect that the allowance demand of a firm for hedging requirements might be endogenously determined in response to changing expectations on input prices as suggested in Schopp and Neuhoff (2013).

Further, Tietjen et al. (2019) point out that risk averse firms might apply a lower interest rate in times when their private bank is sufficiently large, i.e., when the TNAC exceeds the hedging requirements. Policy interventions such as the recent EU ETS reform increase uncertainty and might further impact the interest rate applied by firms in the market (Salant, 2016). Thus, in order to understand the economic impacts of the EU ETS reform even better, the interplay between interest rate, hedging requirements and governmental regulations should be the subject of further research.

5. The Reformed EU ETS in Times of Economic Crises: the Case of the COVID-19 Pandemic

5.1. Introduction

Since January 2020, COVID-19, also referred to as Coronavirus, is changing people's everyday lives all around the globe. The repercussions of the pandemic are observable on the stock and commodity markets worldwide.[65] 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, 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 the energy-intense industry, the electricity sector, and inner-European aviation are capped by the EU ETS.

Since 2005, the EU ETS accounts for more than 45% of emissions in the EU, the 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 in low-carbon technology (Bel and Joseph, 2015) - but also

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

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, 2014c). One 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 (CM) 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 CM, 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 CM should ensure price stability and price predictability (European Commission, 2014d). 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, this chapter 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 Chapter 4 by 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.[66]

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 a 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, the firm's expectation on baseline emissions 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 CM, 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 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 this thesis is able to retrieve the respective volumes endogenously. Thereby, the modeling 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 are perfectly rational, the paper at hand differs from their approach as it acknowledges that firms are shortsighted and are bound to hedging constraints. Both forms of bounded rationality are important to consider when evaluating the impact of the Corona crisis on market outcomes, as Bocklet and Hintermayer (2020) find that only models that incorporate myopia and hedging requirements are able to explain historical outcomes in the

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

EU ETS. 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 in 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 emissions 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 persists, the less powerful is 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 MSR and CM) 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 this chapter is organized as follows: In Section 5.2, 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 5.3, the theoretical implications of a generic economic shock are discussed and embedded into the literature. Section 5.4 analyses the impact of the COVID-19 pandemic on numerical outcomes in the EU ETS. To do so, the model is parameterized (Section 5.4.1) and different shock scenarios are introduced (Section 5.4.2). The numerical results are shown in Section 5.4.3. In Section 5.5, the current policy framework is evaluated by analyzing the impact of the COVID-19 crisis on aggregate emissions and the market's price respond towards the economic shock. As the numerical results strongly depend on the underlying parameter assumption, they are validated by sensitivity analyses (Section 5.6). Section 5.7 concludes.

5.2. 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, 2014c). Both forms of bounded rationality have also been the 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-averse (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 chapter accounts for myopia and exogenous hedging requirements and hereby closely resembles the model developed in Chapter 4.

5.2.1. 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 consists 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, such as an economic crisis, occurs.

Formally, a firm solves the intertemporal cost minimization problem $\mathcal{M}(\tau, \mathcal{H})$

$$
\begin{aligned}
\min \quad & \sum_{t=\tau}^{\tau+H} \frac{1}{(1+r)^t}[C(e(t)) + p(t)x(t)] \\
& s.t.\; b(t) - b(t-1) = x(t) - e(t) \quad \text{for all} \quad t = \tau, \tau+1, \ldots, \tau+H \\
b(t) \geq \quad & \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t}-t) \cdot e(\tilde{t}), \\
& x(t),\, e(t) \gtreqless 0.
\end{aligned}
\tag{5.1}
$$

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[67], 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 averse, 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 $\tilde{t}$.

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

From Equation 5.1, the corresponding Lagrangian is derived (see D.1) 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 condi-

[67]While Schmidt (2020) scales the slope of the MAC 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)

tions and is convex, the Karush-Kuhn Tucker (KKT) conditions are sufficient to derive the following optimality conditions:

$$c(t)[u(t) - e(t)] = p(t). \tag{5.2}$$

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

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1}\frac{\mu_b(t)}{p(t)}. \tag{5.3}$$

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.[68] Once the hedging requirement binds, prices can deviate from the Hotelling rule and may therefore increase at a lower rate.[69]

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 CM, 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:

$$S_{auct}(t) = S_{auct}(t-1) - a(t)S_{auct}^{0} - MSR_{Intake}(t) + MSR_{Reinjection}(t). \tag{5.4}$$

The parameter $a(t)$ hereby presents the annual LRF that ensures that allowance supply is reduced over time from the initial allowance supply S_{auct}^{0}.[70]

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

[69] 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).

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

If the TNAC[71] - 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}.[72] 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

$$MSR_{Intake}(t) = \begin{cases} \gamma(t) \cdot TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{5.5}$$

and

$$MSR_{Reinjection}(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else.} \end{cases} \tag{5.6}$$

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

$$Cancel(t) = \begin{cases} MSR(t) - S_{auct}(t-1) & \text{if } MSR(t) \geq S_{auct}(t-1), \\ 0 & \text{otherwise.} \end{cases} \tag{5.7}$$

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

5.2.3. 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,

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

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

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 5.1) 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.

5.3. Theoretical Considerations and Relevant Literature

With the introduction of the MSR and the CM, 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 5.5 and 5.6), 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 5.2), 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 the 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 5.5, 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 volume 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.[73] 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 will thereby reduce 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 CM.

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 the 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 a way, that the cut-off date is postponed and the MSR volumes is increased so much that the CM is triggered in the following year(s).[74]

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 the 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

[73]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).

[74]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%.

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 lasts for one year, mitigates the waterbed effect most, as the shock has not at all been incorporated 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 the "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.

5.4. Impact of the COVID-19 Pandemic on the EU ETS

Since it is not possible to depict the general effects of an 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 5.2 is parameterized (Section 5.4.1). 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 5.4.2). Given the parameterization and using these five scenarios, the model is implemented as a Mixed-Integer Problem in GAMS and solved with CPLEX. The numerical results are shown in Section 5.4.3.

5.4.1. Parameterization

Besides the regulatory parameters provided by the policy maker that are shown in Section 5.2, assumptions on the interest rate, the cost parameter, the hedging schedule, and the planning horizon are provided.

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.[75]

Exogenous Parameter Assumptions

In line with e.g. Bocklet et al. (2019) - see Chapter 3 - , I apply an interest rate of $r = 8\%$. The interest rate reflects the profitability and hence the opportunity cost of abatement.[76]

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 Chapter 4: an 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.[77]

Further, as firms in the EU ETS plan ahead with a "limited time horizon" (European Commission (2014c), 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.

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.[78] 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 assumes 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

[75] As the underlying parameter assumptions do not change the modus operandi of the model but are critical for numerical results, sensitivity analyses for the exogenous parameter assumptions are provided in Section 5.6.1.

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

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

[78] 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.

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

$$u(t) = economic\ activity\ index(t) \cdot energy\ intensity\ index(t) \cdot carbon\ intensity\ index(t). \tag{5.8}$$

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 5.1). In order to justify the application of 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 Basse 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 of 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 balanced each other out (ODYSSEE-MURE, 2020) - the TFEC in the industrial sector declines in the respective time period mostly due to 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 5.1). 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 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 assumption 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 the 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 5.1 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

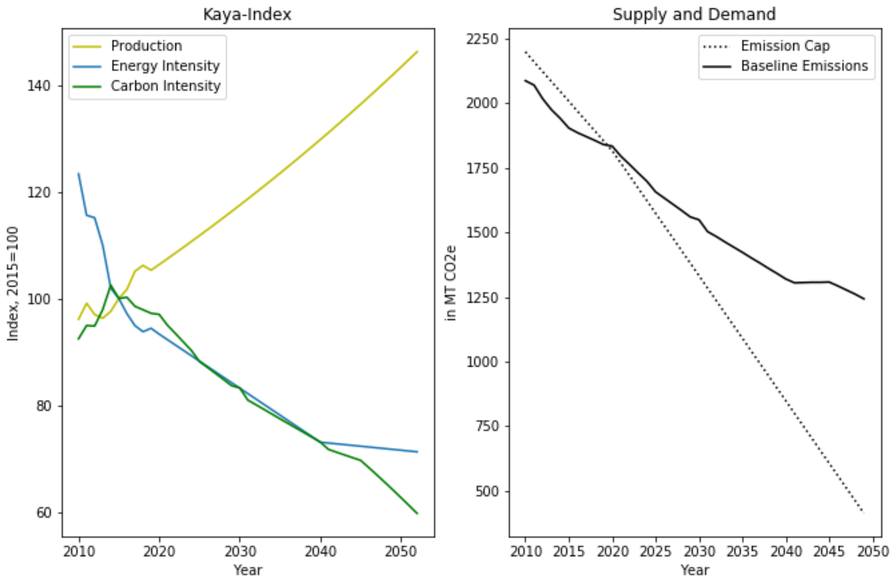

Figure 5.1.: Kaya indices, baseline emissions and emission cap in the no-shock scenario

in 2010[79] they decrease to 1340 Mt CO_2e in 2050.[80] 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 D.2.

5.4.2. Shock Scenarios

As the precise nature of the COVID-19 induced economic downturn is unknown[81], five scenarios are used to depict likely developments of the economic crisis. The scenarios differ in their assumptions 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 esti-

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

[80] 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 in 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).

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

mation 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)[82]. 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 5.6.1.

A brief description of the parameter assumptions of the five shock scenarios is depicted in Table 5.1. t_{shock}, t_{return} and ΔU hereby indicate the year(s) of the economic shock, the year 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 5.1.: 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 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 $V-Scenario$).[83] After the shock, the economy is expected to reopen within a matter of several months and is 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

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

[83] 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).

(median estimate).[84] 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 pre-reform economic level as late as 2023.[85] 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.[86] 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 emissions remain unaltered by the crisis, as the rebound in economic activity will cause emission 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 a similar or even larger 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

[84] This decline in baseline emissions is 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.

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

[86] 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.

through a U-shaped economic crisis, hence referred to as $U - Scenario$.[87] The $U - Scenario$ is parameterized, so that after the recession in 2020 the economy of the EU ETS countries stagnates from 2021 to 2025. From 2027 onwards, baseline emissions return to the pre-shock trajectory. Therefore, aggregate 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 a 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. An L-shaped economic shock would therefore not be considered temporary, but a permanent one.[88] A permanent shock does not only lead to lower baseline emissions today but to strictly lower baseline emissions at 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 scenarios is depicted in Figure 5.2.[89]

5.4.3. Numerical Results

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

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 5.3. The figure further shows the exogenous assumption on baseline emissions derived by the Kaya identity. As EU ETS regulation, e.g. the LRF and the exogenous allowance supply

[87] 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).

[88] 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.

[89] Note that Figure 5.2 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.

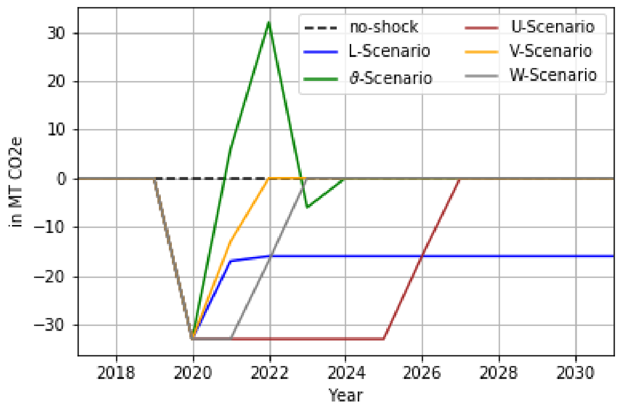

Figure 5.2.: Difference between expected and realized baseline emissions in the shock scenarios

beyond 2030 are not decided yet, I focus on the market results for the third and fourth trading period only.[90]

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 the European Commission, the TNAC dropped from roughly 1700 million allowances in 2018 to 1400 million allowances 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, whereof 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.

[90]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.

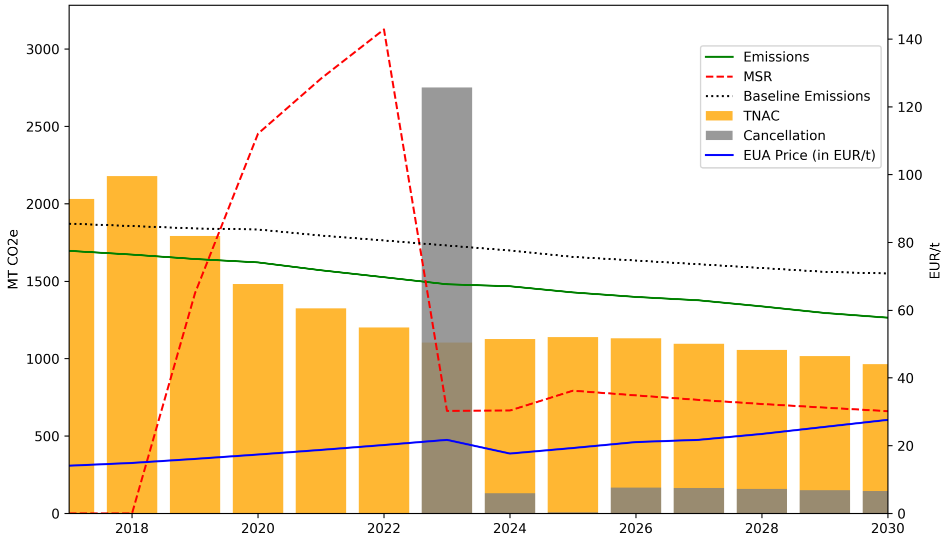

Figure 5.3.: Realized emissions, baseline emissions, TNAC, prices and cancellation in the no-shock market

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.[91] While the absolute price of 17 EUR/EUA in 2019 - and thus before the COVID-19 pandemic - is lower than the real ETS price 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[92], 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 from 24% to 12%, depicted in a downward correction in EUA prices.[93]

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

[92] See Section 5.6.1 for an explanation on how those assumptions impact numerical results.

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

Numerical Results of the Post-Shock Scenarios

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

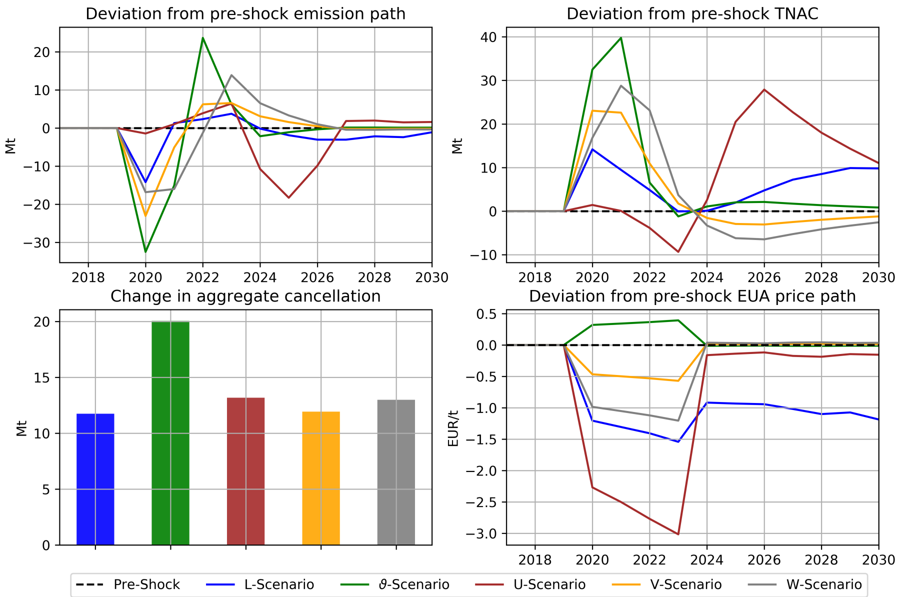

Figure 5.4.: Changes in emissions, TNAC, cancellation volumes and prices in the shock scenarios

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 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 latter, the post-shock allowance prices only meet no-shock prices once the backstop price is reached (2058).

Figure 5.4 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 EUR/EUA in the first eleven months 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 analyzes if the different reactions can be attributed to the changes in the regulatory framework, namely the introduction of the Market Stability Reserve and the Cancellation Mechanism.

5.5. Policy Evaluation

With the introduction of the Market Stability Reserve 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 in low carbon technology (European Commission, 2014d). To discuss if the MSR and the CM are able to fulfill these two goals, the impact of the Corona crisis on aggregate emissions in the EU ETS is evaluated in Section 5.5.1. Further, in Section 5.5.2, I discuss if the MSR increases long-term certainty for investors by stabilizing prices in times of an economic crisis.

5.5.1. 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.,

$$ERI = |\frac{\Delta Cancel}{\Delta U}|. \tag{5.9}$$

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

Table 5.2 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.[94]

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.[95]

While long-run emissions are reduced in all scenarios, the size of the remaining waterbed widely differs: in the $V - Scenario$, the MSR and CM 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

[94] Note, that due to different assumptions 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).

[95] 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 account for a potential rebound effect of the economy. Once one accounts for a more diverse set of crises scenarios, such as a potential overshoot of the economy after the crisis, the causality found by Azarova and Mier (2020) is no longer valid.

short run but hardly impacts aggregate emissions at all: only 1% of the reduction in baseline emissions translates into long-run emission' 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 times 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 effect 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 5.3.

Overall, the results indicate that some of the short-run emissions reductions 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 times 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 5.6.1).

5.5.2. 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 market's 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, 2014d).

So far, scientific literature has not found a common measurement of 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 Market Stability Reserve design prior to the introduction of the Cancellation Mechanism. In absence of the CM, the MSR simply shifts allowances to the future and preserves them over time.

To analyze if the MSR alongside the CM stabilizes 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

$$RPS = \sum_{t=\tau}^{\tau+H} \frac{1}{H} \left| \frac{p_t(t_{shock}) - p_t(t_{no-shock})}{p_t(t_{shock})} \right|. \tag{5.10}$$

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 CM are not included in the model yet. This implies that Equations 5.5 - 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 5.4 reduces to $S_{auct}(t) = S_{auct}(t-1) - a(t)S^0_{auct}$.[96]

The numerical findings of the RPS for $\tau = 2020$ and $H = 10$ are depicted in Table 5.3. 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

[96]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.

prices.[97] 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 time ($t_{p-return}$) onwards, realized prices are consistent with the price expectations of firms before the reform.[98]

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 5.3.: 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.

5.6. 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 5.6.1). 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 5.6.2).

[97] 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.

[98] 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.

5.6.1. 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.

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.

Size of the Shock

As there is high uncertainty about the severity of the shock, the following sensitivities are provided for an emission reduction 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)[99]. For the high estimate, overall baseline emissions are reduced by 75 Mt CO_2e.[100] 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.[101] On the contrary, if the short-run emission reduction of the Corona crisis is rather low (i.e., low estimate), relatively fewer emissions will also be saved in the future (ERI=19%).

Myopia

Since planning horizons of firms widely vary among industries, firm 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 5.4.3 for a planning horizon of 10 years are compared with a shorter planning horizon of 3 years and a longer planning

[99] 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.

[100] 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.

[101] This is also in line with the findings in Schmidt (2020) which show that larger overlapping policies lead to larger cancellations.

horizon of 15 years corresponding to the potential planning horizons of small- or medium-sized manufacturing firms (Stonehouse and Pemberton, 2002) and large publicly traded manufacturing firms (Souder et al., 2016), respectively.

Assuming a shorter (longer) planning horizon than in the base case leads to lower (higher) prices at 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 larger, 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 Corona induced emissions 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 an crisis.

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 to the results of an 60% hedging schedule, i.e., 60% of the allowance sales are hedged one year ahead, 30% two years 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 cancellations 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.

5.6.2. Shortcomings

The paper at hand relies on simplifying assumptions 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 decisions 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 variables endogenously.

Further research should therefore be conducted regarding the endogenous interplay of economic shocks, risk aversion, and uncertainty.

5.7. Conclusion

This chapter of the thesis at hand analyzes the implications of economic crises on market outcomes in the reformed EU ETS. As the precise market outcomes strongly differ in regards to 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 all 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 than 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 the additional cancellation and the lower aggregate emissions in the EU ETS.

Second, while the MSR and the CM 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 of 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 is 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 CM, are indeed able to decrease price risk in light of an economic crisis.

Since 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.

A. Supplementary Material for Chapter 2

A.1. Overview of Sectors on the Carbon Leakage List

Table A.1 provides an overview of the number of four-digit NACE sectors included in each two digit NACE sector on the CLL in Phase III and in Phase IV, as published by the European Commission in 2014 and 2019, respectively. The capital intensity is measured as the gross stock of fixed assets per employee in thousand EUR based on data of German key industries estimated by Löbbe (2009), where available. The German industrial classification system (WZ) is therefore matched to the respective NACE code. The share of a sector's historical emissions on all EU ETS emissions in 2019 is provided by Eurostat (2021). For the sectors 0500-088, 1100-1200, 1300-1500, and 3100-3200 data was only available for the respective sectors combined. Thus, unweighted averages are used for simplification.

Table A.1.: Overview of sectors on the CLL, capital intensity and emission share in %.

NACE code	**Two-digit sector**	**CLL Phase III**	**CLL Phase IV**	**Capital intensity**	**Emission share**
0500	*Mining of coal and lignite*	1	1	365*	0.4*
0600	*Extraction of crude petroleum and natural gas*	2	1	365*	0.4*
0700	*Mining of metal ores*	2	2	258*	0.4*
0800	*Other mining and quarrying*	2	2	258*	0.4*
1000	*Manufacture of food products*	5	3	113*	1.0*
1100	*Manufacture of beverages*	4	1	113*	1.0*
1300	*Manufacture of textiles*	10	3	191	0.1*
1400	*Manufacture of wearing apparel*	8	1	89	0.1*
1500	*Manufacture of leather and related products*	3	0	n/a	0.1*
1600	*Manufacture of wood (products) and of cork products*	2	1	104	0.2
1700	*Manufacture of paper and paper products*	3	2	224	1.1
1900	*Manufacture of coke and refined petroleum products*	2	2	845	4.9
2000	*Manufacture of chemicals and chemical products*	11	8	271	5.3
2100	*Manufacture of basic pharmaceutical products*	2	1	n/a	0.2
2200	*Manufacture of rubber and plastic products*	2	0	109	0.4
2300	*Manufacture of other non-metallic mineral products*	16	11	187	7.2
2400	*Manufacture of basic metals*	11	10	200	6.3
2500	*Manufacture of fabricated metal products*	1	0	81	0.5
2600	*Manufacture of computer and electronic products*	10	1	106	0.1
2700	*Manufacture of electrical equipment*	10	0	98	0.2
2800	*Manufacture of machinery and equipment n.e.c.*	21	0	95	0.4
2900	*Manufacture of motor vehicles and (semi-) trailers*	2	0	176	0.4
3000	*Manufacture of other transport equipment*	6	0	128	0.1
3100	*Manufacture of furniture*	1	0	103	0.1*
3200	*Other manufacturing*	9	0	103	0.1*

*data only available as average of two or more NACE sectors.

B. Supplementary Material for Chapter 3

B.1. Optimization Problem of the Firm

Assuming a perfectly competitive allowance market the optimization problem of a rational firm with perfect foresight is given as

$$
\begin{aligned}
\min \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[\frac{c}{2}(u-e(t))^2 + p(t)x(t)] \\
s.t. \quad & b(t) - b(t-1) - x(t) + e(t) = 0 \quad \text{for all} \quad t = 1, 2, \ldots, T \\
& b(t) \geq 0 \\
& x(t),\, e(t) \gtrless 0.
\end{aligned}
\tag{B.1}
$$

By assigning Lagrange multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow constraint and the positivity constraints, respectively, we derive the following Lagrangian function:

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

As the optimization problem is convex and fulfills the Slater condition, we know that the corresponding KKT conditions are necessary and sufficient for optimality. We derive these conditions by the above Lagrangian function for all $t = 0, 1, 2, \ldots, T$:

Stationarity conditions:

$$\frac{\partial \mathcal{L}}{\partial x(t)} = \frac{1}{(1+r)^t} p(t) - \lambda(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.3}$$

$$\frac{\partial \mathcal{L}}{\partial e(t)} = (-1)\frac{1}{(1+r)^t} c(u - e(t)) + \lambda(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.4}$$

$$\frac{\partial \mathcal{L}}{\partial b(t)} = \lambda(t) - \lambda(t+1) - \mu_b(t) = 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.5}$$

Primal feasibility:

$$b(t) - b(t-1) - x(t) + e(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.6}$$

$$x(t),\ e(t) \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.7}$$

Dual feasibility and complementarity:

$$0 \leq b(t) \perp \mu_b(t) \geq 0 \quad \forall\, t = 1, 2, \ldots, T \tag{B.8}$$

$$\lambda(t) \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{B.9}$$

B.2. The Impact of Backstop Costs

Lemma *Different backstop costs do not change the level of emissions, abatement, TNAC, MSR or cancellation. Only the price path shifts up- or downwards with higher or lower backstop costs, respectively.*

Proof Let bc be some backstop costs, with corresponding cost parameter $c(t)$ and optimal emissions $e(t)$, abatement $u - e(t)$, $TNAC(t)$, $MSR(t)$ and $Cancel(t)$ and the price level $p(t)$. We know that these variables fulfill both the individual KKT conditions of the firm stated in Appendix B.1 and the regulatory conditions from sections 3.2.2 and 3.2.3.

Now let $\tilde{bc}$ be some other backstop costs. We now want to show that the individual KKT conditions from Appendix B.1 and the regulatory conditions are fulfilled for the same variables and a scaled version of the price path. From the definition of backstop costs, we know that $\tilde{c} = \frac{\tilde{bc}}{u} = \frac{\tilde{bc}}{bc}c$. We further define

$$\begin{aligned}
\tilde{p}(t) &:= \frac{\tilde{bc}}{bc} p(t) \\
\tilde{\lambda}(t) &:= \frac{\tilde{bc}}{bc} \lambda(t) \\
\tilde{\mu_b}(t) &:= \frac{\tilde{bc}}{bc} \mu_b(t).
\end{aligned}$$

Then we can easily check that $\tilde{p}(t), \tilde{\lambda}(t)$ and $\tilde{\mu_b}(t)$ together with the unchanged quantities $e(t)$, $TNAC(t)$, $MSR(t)$ and $Cancel(t)$ satisfy all KKT conditions and regulatory market conditions. Hence they give a solution to the problem with backstop costs $\tilde{bc}$ with the same values for the quantities and a scaled price path $\tilde{p}(t)$.

As the lemma states, the concrete parameter of the cost function does not affect the underlying mechanisms of the EU ETS. Only the absolute price level changes with $\frac{\tilde{p}(t)}{p(t)} = \frac{\tilde{bc}}{bc}$. The lemma also holds true for other definitions of c as long as $c \cdot u$ is not affected by the change of the backstop costs. In particular it also holds true for time dependent $u(t)$ and $c(t)$ as long as $u(t) \cdot c(t)$ is not affected.

B.3. Effect of the CM with a Reduced LRF

In Figure B.1 we compare the effect of a CM with the amended LRF of 2.2% to the effect of a CM given the pre-reform intake rate of 1.74%. The results indicate that the CM only slightly decreases emissions and increases prices in the short run. The change in the LRF however, is the main price driver and responsible for the long-run emission reduction.

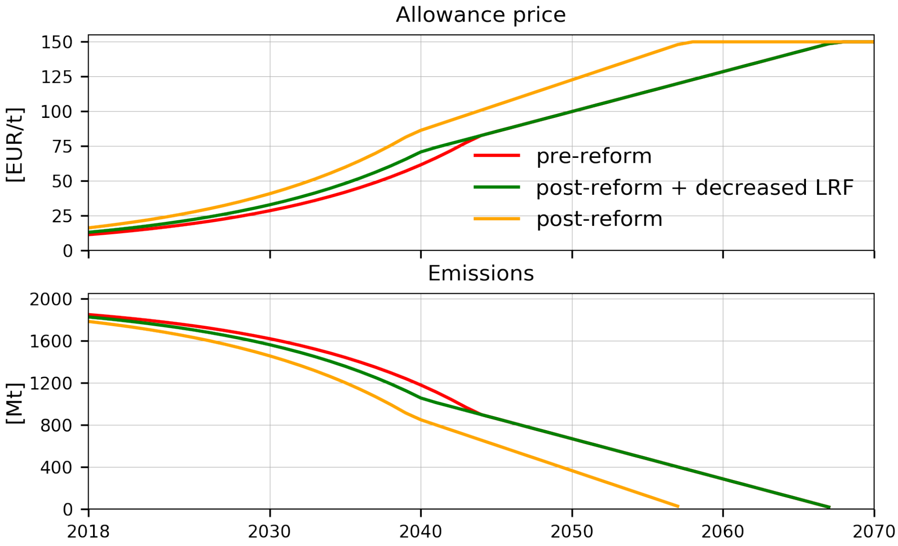

Figure B.1.: Effect of the CM

C. Supplementary Material for Chapter 4

C.1. Lagrangian with Hedging Requirements

For the optimization problem $\mathcal{M}$ (Equation 4.1) with the hedging constraint depicted in Equation 4.9 we can derive the corresponding Lagrangian by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the banking flow constraint and the hedging constraints[102], respectively:

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

As the Slater conditions are fulfilled for the optimization problem, the KKT conditions give sufficient and necessary conditions for an optimum. From Eq. C.1, the stationary conditions are derived:

$$\frac{\partial \mathcal{L}}{\partial x(t)} = \frac{1}{(1+r)^t}p(t) - \lambda(t) = 0 \quad \forall\, t = 1,2,\ldots,T \tag{C.2}$$

$$\frac{\partial \mathcal{L}}{\partial e(t)} = (-1)\frac{1}{(1+r)^t}c(u-e(t)) + \lambda(t) + \sum_{\tilde{t}=0}^{t} hedgeshare(t-\tilde{t})\mu_b(\tilde{t}) = 0 \quad \forall\, t = 1,2,\ldots,T \tag{C.3}$$

$$\frac{\partial \mathcal{L}}{\partial b(t)} = \lambda(t) - \lambda(t+1) - \mu_b(t) = 0 \quad \forall\, t = 1,2,\ldots,T. \tag{C.4}$$

[102] Note that the base model without hedging constraints is equivalent to the model with hedging constraints for $hedgeshare(\tilde{t}-t) = 0$.

Primal feasibility:

$$b(t) - b(t-1) - x(t) + e(t) = 0 \quad \forall\, t = 1, 2, \ldots, T \tag{C.5}$$

$$x(t),\ \ e(t) \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{C.6}$$

Dual feasibility and complementarity:

$$0 \leq b(t) - \sum_{\tilde{t}=t}^{T} hedgeshare(\tilde{t} - t) e(\tilde{t}) \perp \mu_b(t) \geq 0 \quad \forall\, t = 1, 2, \ldots, T \tag{C.7}$$

$$\lambda(t) \ \gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. \tag{C.8}$$

D. Supplementary Material for Chapter 5

D.1. Lagrangian with Myopia and Hedging Requirements

For the optimization problem $\mathcal{M}(\tau, \mathcal{H})$ (Equation 5.1) the corresponding Lagrangian is derived by assigning multipliers $\lambda(t)$ and $\mu_b(t)$ to the respective banking flow constraint and the hedging constraints:

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

D.2. 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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CURRICULUM VITAE

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PERSONAL DATA

Date of Birth	January 1, 1991
Place of Birth	Koblenz
Nationality	German

RESEARCH INTERESTS

Emissions trading, carbon pricing, climate policy, electricity markets

EDUCATION

since 10/2016	**Department of Economics, University of Cologne** Doctoral Candidate in Economics
09/2014 - 04/2016	**University of Alaska, Fairbanks** Master of Science in Resource and Applied Economics
10/2011 - 05/2014	**Ruprecht-Karls University Heidelberg** Bachelor of Science in Economics
08/2013 - 12/2013	**University of Alaska, Fairbanks** Study abroad
03/2010	**Görres Gymnasium Koblenz** Abitur

WORKING EXPERIENCE

since 10/2016	**Chair for Political Economy and Energy Economics, University of Cologne** Researcher
05/2016 - 09/2016	**Information Insights Inc**, Fairbanks Project consultant
08/2015 - 05/2016	**School of Management, University of Alaska Fairbanks** Instructor and teaching assistant
08/2014 - 07/2015	**School of Management, University of Alaska Fairbanks** Teaching assistant
03/2014 - 08/2014	**SAP SE**, Walldorf Working student
06/2012 - 01/2014	**Ruprecht-Karls University Heidelberg** Research assistant
03/2013 - 05/2013	**German Parliament**, Berlin Inter

LANGUAGES

German	Native
English	Fluent
French	Conversational
Spanish	Basic

PUBLICATIONS

Articles in Peer-Reviewed Journals:

- J. Bocklet, M. Hintermayer, L. Schmidt, T. Wildgrube (2019). The Reformed EU ETS – Intertemporal Emission Trading with Restricted Banking. *Energy Economics*, Vol. 84, Article 104486. DOI: 10.1016/J.ENECO.2019.104486.
- J. Bocklet & J. Baek (2017). Do Oil Price Changes Have Symmetric or Asymmetric Effects on the Unemployment Rate?: Empirical Evidence from Alaska. *Energy Sources, Part B: Economics, Planning and Policy*, DOI: 10.1080/15567249.2016.1152326.

Working Papers:

- J. Bocklet (2020). The Reformed EU ETS in Times of Economic Crises: the Case of the COVID-19 Pandemic. *EWI Working Paper* 20/10.
- J. Bocklet & M. Hintermayer (2020). How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule. *CESifo Working Paper* 8579.
- J. Bocklet & M. Hintermayer (2020). How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule. *EWI Working Paper* 20/01.
- J. Bocklet, M. Hintermayer, L. Schmidt, T. Wildgrube (2019). The Reformed EU ETS – Intertemporal Emission Trading with Restricted Banking. *EWI Working Paper* 19/04.

Further Publications:

- J.Bocklet (2018). Climate Change: Learning to Negotiate on Behalf of the Planet. *Open Access Government*, July 2018,(312-313).

TEACHING AND SELECTED CONFERENCE PRESENTATIONS

2017 - 2020	**Model UNFCCC - Strategic Climate Change Role Play** *Seminar* (graduate level) University of Cologne in cooperation with CEMS
2019	**Bachelor Seminar in Energy Economics** *Seminar* (undergraduate level) University of Cologne **The Amendment of the EU ETS: Decomposition of Effects and Dynamic Efficiency** Presentation at *12th RGS Doctoral Conference in Economics*, February 2019 Ruhr-University Bochum **The Reformed EU ETS: Intertemporal Emission Trading with Restricted Banking** Presentation at *4NEMO Summer School*, August 2019 ifo Institute, Munich
2018-2019	**Microeconomics I: Demand, Supply and Equilibrium** *Lecture* (graduate level) University of Cologne
2017-2019	**Microeconomics I: Demand, Supply and Equilibrium** *Exercise session* (graduate level) University of Cologne
2016-2017	**Energy Markets and Regulation** *Exercise session* (graduate level) University of Cologne
2015-2016	**Econ 202: Macroeconomics** *Lecture and exercise session* (undergraduate level) University of Alaska Fairbanks
2014 -2015	**Econ 227: Intermediate Statistics for Business and Economics** *Exercise session* (undergraduate level) University of Alaska Fairbanks

2014 **Econ 100: Political Economy**
Exercise session (undergraduate level)
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AWARDS AND CERTIFICATES

- Teaching rated 1.0 based on the student evaluation of the seminar "Model UNFCCC, Climate Change Strategy Role Play" (2020)
- Nomination for the Distinguished CESifo Affiliated Award for the paper "How Does the EU ETS Reform Impact Allowance Prices? The Role of Myopia, Hedging Requirements and the Hotelling Rule" (2020)
- Recipient of the CEMS Outstanding Contribution Award for the course "Model UNFCCC, Climate Change Strategy Role Play" (2019)
- Recipient of the Phi Kappa Phi Honor to rank within the top 10 % of graduates (2016)