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Contents

List of Figures ix

List of Tables xi

Abbreviations xi

1. Introduction 1

1.1. Motivation . . . 1

1.2. Outline . . . 3

1.2.1. A note on the effect of learning by doing in different carbon pricing regimes . . . 3

1.2.2. The reformed EU ETS - Intertemporal emission trading with restricted banking . . . 3

1.2.3. Fit for 55? An assessment of the effectiveness of the EU COM's reform proposal for the EU ETS . . . 4

1.2.4. Complementing carbon prices with Carbon Contracts for Difference in the presence of risk - When is it beneficial and when not? . . . 4

1.3. Methodological approaches . . . 5

2. A note on the effect of learning by doing in different carbon pricing regimes 7

2.1. Introduction . . . 7

2.2. Marginal effect of learning by doing on abatement . . . 10

2.2.1. Carbon tax . . . 11

2.2.2. Emission trading system . . . 13

2.3. Total costs under learning by doing . . . 18

2.4. Conclusion . . . 22

3. The reformed EU ETS - Intertemporal emission trading with restricted banking 25

3.1. Introduction . . . 25

3.2. Discrete dynamic optimization model 28
3.2.1. Decision-making of a representative firm 28
3.2.2. Market equilibrium 29
3.2.3. Introduction of the MSR and the CM 30
3.2.4. Model implementation and parametrization 31
3.3. Results and Sensitivity Analysis 32
3.3.1. Results under the current regulation 33
3.3.2. Sensitivity analysis 34
3.3.3. Results in the context of previous studies 38
3.4. Impact of the EU ETS amendments on emissions, prices and economic performance 39
3.4.1. Decomposition of effects of the recent EU ETS amendments on prices and emissions 39
3.4.2. Cost effectiveness 42
3.5. Conclusion 44

4. Fit for 55? An assessment of the effectiveness of the EU COM's reform proposal for the EU ETS 47
4.1. Introduction 47
4.2. The EU ETS in its current regulation and with the reform proposal 50
4.2.1. Linear reduction factor 51
4.2.2. Market Stability Reserve 51
4.2.3. Cancellation Mechanism 52
4.3. Modeling the EU ETS reform proposal 52
4.3.1. Firms' decision 53
4.3.2. Market equilibrium 54
4.3.3. Market Stability Reserve and Cancellation Mechanism . . 55
4.3.4. Model implementation and parametrization 56
4.4. Results 57
4.4.1. Increased linear reduction factor 58
4.4.2. Revised MSR regulation 59
4.4.3. Revised Cancellation Mechanism 62
4.4.4. Scenario comparison 64
4.5. Discussion 65
4.5.1. Critical model assumptions 65
4.5.2. Potential shortcomings of the proposed reform elements . 67
4.6. Conclusion 69

5. Complementing carbon prices with Carbon Contracts for Difference in the presence of risk **71**
5.1. Introduction 71
5.2. Carbon pricing regimes in the absence of risk 75
5.2.1. Model framework in the absence of risk 76
5.2.2. Policy ranking in the absence of risk 80
5.3. Carbon pricing regimes in the presence of risk 82
5.3.1. Model framework in the presence of risk and socially optimal production 82
5.3.2. Policy ranking with damage risk 84
5.3.3. Policy ranking with variable cost risk 88
5.4. Carbon pricing regimes with potentially socially not optimal production 93
5.4.1. Model framework in the presence of risk and socially not optimal production 93
5.4.2. Policy ranking with damage risk 94
5.4.3. Numerical application with risk aversion 99
5.5. Discussion 101
5.6. Conclusion 103

A. Supplementary Material for Chapter 2 **107**
A.1. Exogenous cost reduction in period two 107

B. Supplementary Material for Chapter 3 **109**
B.1. Optimization of the Firm, Lagrange Function and KKT Conditions 109
B.2. The Impact of Backstop Costs 110
B.3. Effect of the CM with a Reduced LRF 111

C. Supplementary Material for Chapter 4 **113**
C.1. Sensitivity analysis of the cancellation threshold 113
C.2. Further scenario comparison 114

D. Supplementary Material for Chapter 5 **115**
D.1. Proof of Proposition 5.2.1 115
D.2. Proof of Proposition 5.3.1 117
D.3. Proof of Proposition 5.3.2 120
D.4. Proof of Proposition 5.4.1 124

D.5. Regulatory solutions with variable cost risk and potentially socially not optimal production 128
D.6. Welfare under potentially socially not optimal abatement due to an increase in σ_D 131

Bibliography **133**

List of Figures

2.1. Illustration of the effect of an increase of learning by doing under a carbon tax . . . 13
2.2. Comparison of equilibrium abatement under an exogenous cost reduction and learning by doing . . . 15
2.3. Illustration of the ambiguous effect of an increase of learning by doing . . . 18
2.4. Comparison of tax and ETS if learning by doing is stronger than expected by the regulator . . . 19

3.1. Development of emissions, TNAC, MSR, cancellation and allowance prices . . . 33
3.2. Sensitivity analysis for baseline emissions . . . 35
3.3. Effect of baseline emissions on cancellation . . . 36
3.4. Sensitivity analysis for the interest rate . . . 37
3.5. Effect of interest rate on cancellation . . . 37
3.6. Effect of the change in the Linear Reduction Factor . . . 40
3.7. Effect of the Market Stability Reserve and the Cancellation Mechanism . . . 41
3.8. Comparison of discounted abatement costs and emission levels in different scenarios . . . 43

4.1. Ex-ante allowance supply under the 2018 regulation and the Fit for 55-proposal . . . 58
4.2. Results of *Increased LRF* minus *2018 regulation* . . . 59
4.3. MSR intake under *Increased LRF* and *New MSR* . . . 60
4.4. Results of *New MSR* minus *Increased LRF* . . . 61
4.5. Ex-post allowance supply under *Increased LRF* and *New MSR* . . . 62
4.6. Cancellation volume under 2018 regulation and Fit for 55-proposal 63
4.7. Results of *Fit for 55* minus *New MSR* . . . 63
4.8. Achieved versus target reduction for 2030 in the four scenarios . . . 64

4.9. Decomposition of changes in 2021 price level into the individual reform elements 65
4.10. Decomposition of changes in cancellation volume into the individual reform elements 66

5.1. Sequence of actions in the different carbon pricing regimes. . . . 78
5.2. Market clearing. 79
5.3. Density of D and C_v following a truncated normal distribution with $P(C_v > D) = 0$. 82
5.4. Difference in welfare compared to social optimum in the presence of damage risk. 88
5.5. Difference in welfare compared to social optimum in the presence of cost risk. 92
5.6. Density of normally distributed D and C_V with $P(C_V > D) > 0$. 94
5.7. Difference in welfare compared to social optimum in the presence of damage risk and potentially welfare-reducing production. . . . 99
5.8. Difference in welfare compared to social optimum in the presence of damage risk, potentially welfare-reducing production and risk aversion. 100

B.1. Effect of the Cancellation Mechanism 112

C.1. Cancellation volume under different cancellation thresholds . . . 113
C.2. Decomposition of changes in total emissions into the individual reform elements 114
C.3. Decomposition of changes in 2021 abatement levels into the individual reform elements 114

D.1. Difference in welfare compared to social optimum due to change in $P(c_v > D)$ by altering μ_D in the presence of damage risk and potentially welfare-reducing production. 131

List of Tables

3.1. Overview of examined scenarios 39

4.1. Scenario overview 57

Abbreviations

CCfD	Carbon Contract for Differences
CM	Cancellation Mechanism
CPI	Carbon pricing instrument
EU COM	European Commission
EU ETS	European Union Emission Trading System
GHG	Greenhouse gas
MAC	Marginal abatement costs
LRF	Linear reduction factor
MSR	Market Stability Reserve
SCC	Social cost of carbon
TNAC	Total number of allowances in circulation

1. Introduction

1.1. Motivation

Climate change is the most pressing problem humankind is occupied tackling now and for the next decades. It requires immediate action. While it would be ideal to implement first-best policy options, the urgency and problem size of climate change often demands implementing policies that are a political compromise and designed under uncertainty. Practical learnings and experience gained over time help improving policies in place. Research should contribute by proactively evaluating existing climate policies and proposed reforms. A neutral perspective embedded in economic theory and based on scientific standards can inform and support policymakers. In this way, economists should understand themselves as society's plumbers, as Esther Duflo (2017) demands, and help to evolve and refine climate policy.

An increasingly popular approach to climate change mitigation is carbon pricing with 70 systems in place in 2022 (World Bank, 2023). These can be carbon taxes, emission trading systems (ETSs), tradable performance standards or hybrid systems. Carbon pricing is the preferred option for reducing emissions for many jurisdictions as it contributes to distributing emission efforts cost-effectively. In contrast to command-and-control policies, it provides an economic incentive for regulated firms and households to abate their emissions when abatement costs are below the carbon price and choose to emit otherwise. There is no need for governments to decide on which abatement options they should support (in the absence of other market failures).

This research focuses on ETSs and related carbon pricing instruments (CPIs) and how to improve them. ETSs are carbon pricing regimes that set an upper limit on pollution that can be emitted by all regulated entities jointly. This upper limit is operationalized as emission allowances that are auctioned or allocated freely to the market and can be traded among regulated entities. Entities with high abatement costs buy allowances from entities with low abatement costs. The market price of allowances constitutes the carbon price.

While economic theory favors free price discovery on the market, policymakers often prefer to maintain some degree of control over carbon prices. Existing ETSs feature mechanisms that allow policymakers to intervene both to reduce carbon price exposure of firms and households by reducing prices and to incentivize further abatement efforts by tightening prices. For instance, the California Cap-and-Trade Program has an auction reserve price that serves as a minimum carbon price. The Regional Greenhouse Gas Initiative (RGGI), in contrast, features a cost containment reserve that releases allowances to the market if an upper price threshold is reached with the objective to mitigate high prices. The market stability reserve of the European Union Emission Trading System (EU ETS) influences prices in both directions by reducing allowance supply in times of high allowance circulation and increasing supply in times of scarcity (International Carbon Action Partnership, 2022). These interventions may be politically needed but potentially hamper the cost effectiveness of ETSs. Their effects need to be carefully evaluated to fine-tune policy design options.

Most ETSs cover several periods of time with restricted or unrestricted banking of allowances. Hence, policymakers and economists engaging in plumbing need to understand the dynamics of emissions trading. Different events like economic crises, policy interventions, or cost reductions of abatement technologies can influence future allowance prices. In a dynamic system, these future events have an effect on today's investment and abatement decisions of regulated entities.

The dynamic nature of ETSs exposes firms to carbon price risk that can become a barrier for investment. One approach to manage this risk is for policymakers to offer Carbon Contracts for Differences (CCfDs) to firms. CCfDs are contracts that pay out the difference between a guaranteed strike price and the actual carbon price per abated emissions by an investment and hence hedge firms against carbon price risk. Similarly to direct price interventions in ETSs, potentially adverse effects of CCfDs need to be carefully assessed.

The dissertation hopes to contribute to improving the design of ETSs and related carbon pricing instruments. Its leading questions are: Are the design options for CPIs that are currently discussed effective and efficient? How does the dynamic nature of emission trading drive its outcome compared to other CPIs?

Four chapters discuss these questions. Chapter 2 presents an analytical model to investigate the effect of learning by doing on the intertemporal distribution of abatement efforts and total costs in an ETS and under a carbon tax. Chapters 3 and 4 analyze the 2018 reform and the 2021 reform proposal of the EU ETS. Chapter 5 analyzes under which circumstances CCfDs are useful instruments to complement ETSs. Each chapter presents one of the following academic articles. In case of work authored by multiple researchers, the authors contributed equally:

1. A note on the effect of learning by doing in different carbon pricing regimes.
2. The reformed EU ETS - Intertemporal emission trading with restricted banking. Joint work with Johanna Bocklet, Martin Hintermayer and Lukas Schmidt, *EWI Working Paper 19/04* and published in *Energy Economics*. (Bocklet et al., 2019)
3. Fit for 55? An assessment of the effectiveness of the EU COM's reform proposal for the EU ETS, *EWI Working Paper 22/04* and submitted to *Zeitschrift für Energiewirtschaft.* (Wildgrube, 2022)

4. Complementing carbon prices with Carbon Contracts for Difference in the presence of risk - When is it beneficial and when not? Joint work with Samir Jeddi and Dominic Lencz, *EWI Working Paper 21/09.* (Jeddi et al., 2021)

The remainder of the introduction provides an outline of each chapter (section 1.2) and discusses methods applied as well as opportunities for future research (section 1.3).

1.2. Outline

1.2.1. A note on the effect of learning by doing in different carbon pricing regimes

Market-based climate policy instruments have emerged in a large number of jurisdictions all over the world. While all types of carbon pricing help reduce emissions efficiently, there is still a lack of understanding of how carbon taxes and emission trading systems work in dynamic settings. This research contributes to closing this gap by analyzing how learning by doing influences the abatement path and total costs under the two carbon pricing regimes. An analytical two-period model finds that while learning by doing increases early abatement under a carbon tax, the effect is ambiguous under an emission trading system; i.e., period-one abatement can either increase or decrease. This is caused by two opposing effects: A *learning effect* incentivizes early abatement as this reduces future costs. A *Hotelling effect*, in contrast, incentivizes emitters to wait as they expect costs to decrease over time if learning by doing takes place. The latter effect does not occur under a carbon tax. It cannot be determined which effect is dominant without knowing the specific abatement cost function. If the regulator sets the emissions cap or tax level under uncertainty and learning by doing is stronger than expected, total costs are higher under a carbon tax than under an ETS. If learning by doing is weaker, a carbon tax performs better. The results highlight the importance of understanding learning by doing in order to target correct carbon price levels.

1.2.2. The reformed EU ETS - Intertemporal emission trading with restricted banking

With the increase of the linear reduction factor, the implementation of the market stability reserve and the introduction of the cancellation mechanism, the EU ETS changed fundamentally. Chapter 3 develops a discrete time model of the inter-temporal allowance market that accurately depicts these reforms assuming that prices develop with the Hotelling rule as long as the aggregated bank is non-empty. A sensitivity analysis ensures the robustness of the model results regarding its input parameters. The accurate modelling of the EU ETS allows for a decomposition of the effects of the individual amendments and the evaluation of their cost effectiveness. The market stability reserve shifts emissions to the future but is allowance preserving. A one-time cancellation reduces the overall emission cap, increasing allowance prices in the long run, but does not significantly impact the emission and price path in the short run. The increased linear reduction factor leads with 9 billion cancelled allowances to a stronger reduction than the cancellation mechanism and is therefore the main price driver of the reform.

1.2.3. Fit for 55? An assessment of the effectiveness of the EU COM's reform proposal for the EU ETS

To achieve the EU's new climate target of reducing emissions by at least 55% until 2030, the European Commission proposed a reform of the EU ETS in its 'Fit for 55' legislative package. The reform entails an increase of the linear reduction factor (LRF), an adjustment of the intake rules for the Market Stability Reserve (MSR) and the introduction of a fixed threshold for the cancellation of allowances. Chapter 4 extends the model developed in chapter 3 to assess the impact of the reform as a whole and decompose this impact into the effects caused by the three individual reform elements. The results show a significant impact of the reform with 48% higher prices in 2021 compared to the current regulation. Among other factors, the reform proposal has thereby significantly driven the observed price increase in 2021. The impact of the increased LRF is substantial, while the adjustments of MSR and Cancellation Mechanism are less important. While the proposed reform strengthens the EU ETS, the increased LRF and the adjusted MSR rules do not fully achieve their intended goals. The increased LRF may not reach the intended emissions reduction of 61% for emissions covered under the EU ETS. The adjusted MSR regulation may increase resilience to shocks. Yet, it may also decrease MSR intake, reducing the MSR's ability to regulate allowance supply. The fixed cancellation threshold increases the predictability of the mechanism as intended. However, the changed cancellation volume has repercussions on the achievement of the emission reduction target.

1.2.4. Complementing carbon prices with Carbon Contracts for Difference in the presence of risk - When is it beneficial and when not?

Deep decarbonization requires large-scale irreversible investments throughout the next decade. Policymakers propose Carbon Contracts for Differences (CCfDs) to incentivize such investments in the industry sector. CCfDs are contracts between a regulator and a firm that pay out the difference between a guaranteed strike price and the actual carbon price per abated emissions by an investment. Chapter 5 develops an analytical model to assess the welfare effects of CCfDs and compare it to other carbon pricing regimes. In the model, a regulator can offer CCfDs to risk-averse firms that decide upon irreversible investments into an emission-free technology in the presence of risk. Risk can originate from the environmental damage or the variable costs of the emission-free technology. The chapter finds that CCfDs can be beneficial policy instruments, as they hedge firms' risk, encouraging investments when firms' risk aversion would otherwise inhibit them. In contrast to mitigating firms' risk by an early carbon price commitment, CCfDs maintain the regulator's flexibility to adjust the carbon price if new information reveals. However, as CCfDs hedge the firms' revenues, they might safeguard production with the emission-free technology, even if it is ex-post socially not optimal. In this case, regulatory flexibility can be welfare superior to offering a CCfD.

1.3. Methodological approaches

The thesis at hand applies both analytical and numerical models to understand emission trading and carbon pricing in general. All models in this dissertation describe optimization, i.e., welfare maximization or cost minimization, problems. Analytical models generate general findings but are limited regarding the complexity they can depict as solvability quickly becomes a problem. For instance, numerical models like the ones applied in chapters 3 and 4 of this thesis allow for modeling of non-linearities like regulatory thresholds. All applied models, either analytical or numerical, are partial equilibrium models, assuming no interaction of the analyzed carbon market with other markets.

Chapter 2 develops a simple analytical model for carbon pricing via a tax and via an ETS. With a minimum of specifications for the abatement costs functions applied in the model, the approach achieves findings that can be generalized and applied to most carbon pricing environments. However, the methodology builds on an idealized setting and does not consider constraints that may apply in reality. For instance, the model assumes perfectly rational behavior of firms and regulator as well as decision making under perfect foresight. Future research may relax the assumption of an ideal setting.

Chapters 3 and 4 introduce and develop a numerical model to analyze the market outcome of the EU ETS under different regulatory options. In contrast to the model in chapter 2, this numerical model can accurately depict all design elements of the EU ETS, including non-linear regulatory thresholds. It is a mixed complementary problem (MCP) model using auxiliary binary variables and the big-M constraints to deal with non-linearity. The EU ETS regulation in place with endogeneity of allowance supply and prices features the possibility of multiple solutions to the optimization problem. The numerical EU ETS model minimizes costs and hence presents the solution with maximum emissions given all restrictions.

The ETS models in chapters 2 to 4 assume that ETS prices increase over time with the interest rate building on the seminal work of Hotelling (1931) and Rubin

(1996). For this, the models assume that firms have perfect foresight. Uncertainty about future events would influence the price development in an ETS and change the model results. Chapter 2 analyzes uncertainty of the regulator while keeping the assumption of perfect foresight of firms intact. Especially because ETSs are usually set up as long-term policy instruments, it is clear that assuming perfect foresight is problematic. One option to tackle this problem is to model myopic decision-making with rolling horizons, as in Bocklet and Hintermayer (2020). With this approach, firms learn gradually about future developments. The approach is, however, only applicable in numerical models.

Similarly, the models in chapters 2 to 4 assume perfectly rational firms that base their decision-making on the minimization of costs. This is a reasonable assumption as carbon prices and ETS, in particular, mostly regulate big emitters with access to financial markets. Chapter 5 turns to a setting in which risk and risk aversion of firms lead to inefficient investment choices. Future research should pay more attention to both perfect foresight and rationality. Bounded rationality will become more relevant for carbon pricing as jurisdictions may shift their focus to smaller emitters like households and microenterprises. Similarly, the effect of heterogeneous market participants deserves further research.

In addition to this general discussion of the methodological approaches used in this dissertation, each chapter discusses the respective models and assumptions in detail.

2. A note on the effect of learning by doing in different carbon pricing regimes

2.1. Introduction

In recent years the focus of the climate policy debate has shifted from emission targets to optimal paths for emission reduction. As more countries aim to achieve climate neutrality, the question arises as to how this goal can be reached efficiently and which climate policy measures can support the process at an early or a later stage on the path. Not only does climate policy need to be effective in reaching climate neutrality and but also dynamically efficient in achieving this target. To assess the latter, it is essential to understand how policy instruments incentivize abatement over time and encourage learning and innovation.

The research at hand analyzes the interaction between learning by doing and climate policy; in particular, it assesses how learning by doing influences optimal abatement paths and total costs under a carbon tax and an emission trading system (ETS). Learning by doing is the endogenous reduction of costs of a technology or, in general, an abatement option through the production of this technology or the implementation of the abatement option.[1] The research assesses with the help of an analytical model if carbon taxes and emission trading systems can encourage learning and induce cost reductions.

The amount of research aiming to understand the dynamics of climate policy has significantly increased in recent years. Hintermayer et al. (2020) question the static concept of marginal abatement cost (MAC) curves and show how MAC curves become flatter over time as more abatement options become available. Sinn (2008) assesses how the announcement of a carbon tax can trigger an increase of emissions in the short term and, in an extreme case, lead to more climate damage than without the carbon tax (the effect is known as Green Paradox). This shows that static climate policies can have dynamic effects on other periods. In contrast to carbon taxes, emission trading systems are typically intertemporal instruments that cover several years. While there is no limit on emissions under a carbon tax, the number of emission allowances is finite and usually exhausted under an ETS.[2] The analysis of their dynamics builds on the seminal work of

[1]Wright (1936) provides an early definition of learning as the phenomenon that unit costs are a function of accumulated volume.

[2]Exhaustion could be incomplete in a setup with strong learning effects leading to abatement technologies that are competitive in costs. For instance, Quemin and Trotignon (2018) implicitly argue in this direction by assuming decreasing baseline emissions that become zero in the future even in the absence of the EU ETS.

Hotelling (1931) on the optimal extraction path of finite resources. Hotelling (1931) shows that in an ideal setting extraction adjusts such that gains from extraction develop with the same rate as gains from alternative investments, that is, the interest rate of capital. Cronshaw and Kruse (1996) and Rubin (1996) apply this finding to emission trading systems. Cronshaw and Kruse (1996) are the first to analyze emission trading with banking of allowances. Rubin (1996) extends their analysis to a model in continuous time that allows for banking and borrowing of allowances and shows that ETSs achieve the social optimum.

There is not yet a complete understanding of how climate policies interact with learning by doing. Goulder and Mathai (2000) analyze the effect of learning by doing on optimal abatement paths in the absence of a climate policy (concluding that a carbon tax should follow the shadow benefit of abatement). They find an ambiguous impact of learning by doing on the optimal abatement path: learning by doing can lead to frontloading or postponement of optimal abatement. Nachtigall and Rübbelke (2016) analyze a market in which a renewable energy carrier benefiting from learning by doing competes with a fossil resource under a carbon tax. The fossil resource is finite such that their model shares features of an ETS. Similarly to Goulder and Mathai (2000), they find an ambiguous effect of learning by doing on the deployment of the renewable energy carrier. If learning by doing incentivizes an early fuel switch, the carbon tax does not necessarily cause the Green Paradox. Chakravorty et al. (2011) analyze the effect of learning by doing on the deployment of an alternative low-carbon technology in a Hotelling environment and find that oil extraction under an oligopoly increases in order to keep oil prices low and deter market penetration of the low-carbon technology. In contrast to their setting, the research at hand assumes perfect competition. Barreto and Klaassen (2004) analyze learning by doing in emission trading systems using an energy system optimization model and find that spillover of learning to other regions without ETS increase the benefits of abatement.

The research at hand adds to this literature by analyzing the dynamics of learning by doing under a carbon tax and an emission trading system, comparing the effects under both carbon pricing regimes. It develops an analytical model in which firms decide on the amount of abatement in each of the two periods. The model uses convex but otherwise unspecified abatement cost functions. The model finds that a marginal increase of learning by doing leads to more abatement early on under a carbon tax as early abatement reduces future costs through learning by doing. We can call this *learning effect*. Under an ETS, however, the impact of learning is ambiguous; i.e., abatement can either be frontloaded or postponed. This is because there is an opposing effect beside the *learning effect*. The *Hotelling effect* incentivizes emitters to wait with their efforts as they expect costs to decrease over time if learning by doing takes place. The research presents a graphic illustration of both effects.

The research further adds to the comprehensive strand of literature comparing quantity and price control regimes in environmental policy. This strand builds on the seminal work of Weitzman (1974) who explains that both instruments yield the social optimum under perfect foresight. However, if there is uncertainty regarding pollution damage or abatement costs when introducing a carbon pricing regime, expected outcomes may differ. If in this case the slope of the marginal abatement cost curve is steeper than the slope of the marginal damage curve, a carbon tax, i.e. price control, is preferable. Otherwise, emission trading, i.e. quantity control, leads to a better outcome. Several papers refined and extended these findings. Moledina et al. (2003) analyze a dynamic setting with strategic firms and find that which carbon pricing regime is optimal depends on the type of firm (low versus high costs) that sets the permit price. Newell and Pizer (2008) show that for indexed policies adjusted to emission intensity like tradable performance standards both price- or quantity-based regimes can be preferable, depending on the variation of the output variable used as index and its correlation with emissions.

A substream of this literature strand focuses on dynamic, multi-period settings and how different carbon pricing regimes incentivize abatement and investment in low-carbon technologies. Weitzman (2020) extends his 1974 analysis to a two-period model comparing ETSs with intertemporal banking and borrowing to quantity control with fixed annual caps and price control. He assumes benefits of different periods are independent of each other. In this setup, an intertemporal ETS, that gives firms the freedom to allocate abatement across periods in a cost-minimizing way, does not perform well with regard to benefits. Weitzman (2020) finds that either annual quantity control or price control yield a higher welfare than emission trading. Jung et al. (1996) analyze technology adoption in an industry with heterogeneous firms. They conclude that an ETS outperforms a carbon tax and performance standards. Requate and Unold (2003) and D'Amato and Dijkstra (2015) compare the two carbon pricing regimes in a setting with asymmetric information on technology adoption costs. Requate and Unold (2003) conclude that a carbon tax outperforms an ETS in terms of abatement levels in a case where the regulator commits to a policy without anticipating the development of a new low-carbon technology. The analysis at hand confirms this finding for a setting with learning by doing and draws attention to a situation in which the regulator overestimates learning by doing or technological development in general. In this case, an ETS leads to higher abatement levels and total costs than a carbon tax.

The remainder of the chapter is structured as follows: Section 2.2 develops an analytical two-period model of abatement decisions under carbon pricing where abatement exhibits learning by doing. Section 2.2.1 and section 2.2.2 derive the effect of learning by doing on abatement under a carbon tax and an emission trading system, respectively. Section 2.3 compares total costs under the two carbon pricing regimes in a setting with asymmetric information on the strength of learning by doing. Section 2.4 concludes.

2.2. Marginal effect of learning by doing on abatement

Following Nachtigall and Rübbelke (2016), the research at hand sets up an analytical model with two periods of time in which variables and parameters of period one are denoted by lowercase and of period two by capital letters. Abatement costs follow a convex function of abatement $c(a)$ for which $c_a(a) > 0$[3] and $c_{aa}(a) > 0$ hold.[4] Abatement costs in period two are a function of period-two abatement A and learning by doing $L(a)$. Learning by doing is a function of period-one abatement a. The function $C(A, L(a))$ is convex in A; that is, $C_A(A, L(a)) > 0$ and $C_{AA}(A, L(a)) > 0$. Learning by doing decreases the marginal abatement costs and, in consequence, also total costs in period two; that is, $C_L(A, L(a)) < 0$ and $C_{AL}(A, L(a)) < 0$. The amount of period-one abatement increases learning by doing; that is, $L_a(a) > 0$. As $L_a(a)$ is an auxiliary function with the purpose of making learning by doing analytically visible, we define that $C(A, L(a))$ is linear in $L(a)$. Thus, $C_{LL} = 0$ holds. It is further plausible to assume that $L_{aa} < 0$; i.e., learning by doing decreasing in period-one abatement and the first units of period-one abatement have a stronger impact than the later units. There is no need to further specify the functional form of learning by doing.[5]

The model does not represent spillovers among firms and technologies. It rather assumes implicitly that some degree of spillovers among technologies exist; i.e., using one technology reduces to some extent costs for all technologies in the MAC curve. While the degree of completeness of spillovers scales the impact of learning by doing, the direction of the effect does not change.

Under the two carbon pricing regimes, firms can either abate or pay a carbon price z in period one and Z in period two on their emissions. Given a fixed level of baseline emissions u, constant over time, their choice of abatement determines how much carbon price $z(u - a)$ or $Z(u - A)$ they have to pay in period one and two. Firms minimize the present value of their total costs by choosing abatement levels a and A discounting future costs at interest rate r:

$$TC(a, A, L(a)) = c(a) + z(u - a) + \frac{C(A, L(a)) + Z(u - A)}{1 + r} \tag{2.1}$$

[3]Indices represent the derivation of a function with respect to the variable or parameter in the index.

[4]Convexity of abatement costs is a standard assumption in climate economics and backed by empirical evidence, see for instance Hintermayer et al. (2020).

[5]Most research (see Anzanello and Fogliatto (2011) or Ouassou et al. (2021) for a review) assumes learning occurs in the form of a power function. For instance, the function $f(x) = cx^l$ with $-1 < l < 0$ (Anzanello and Fogliatto, 2011) fulfils the assumptions above. A power function is suitable for learning regarding a specific technology as it allows for more learning in the beginning while the effect becomes weaker with increased experience. The model at hand, however, represents not only one technology but a set of abatement options and learning involves spillovers across these abatement options.

Minimizing equation 2.1 with respect to abatement levels a and A yields the first-order conditions

$$\begin{aligned} TC_a(a, A, L(a)) &= c_a(a) + \frac{C_L(A, L(a))L_a(a)}{1+r} - z \\ &:= f(a, L(a)) \end{aligned} \tag{2.2}$$

$$\begin{aligned} TC_A(a, A, L(a)) &= \frac{C_A(A, L(a))}{1+r} - \frac{Z}{1+r} \\ &:= g(A, L(a)). \end{aligned} \tag{2.3}$$

Equations 2.2 and 2.3 reflect the basic environmental economics finding that the firm optimally chooses the abatement levels such that marginal abatement costs equal the tax rate. For period-one abatement levels a, the firm takes into account the future benefit from early abatement through learning by doing in terms of lower future costs, $\frac{C_L(A,L(a))L_a(a)}{1+r} < 0$. It thus chooses a higher abatement level in period one than it would without learning by doing.

2.2.1. Carbon tax

Under a carbon tax, the carbon price is exogenously set at tax levels $z = t$ and $Z = T$. Implicit differentiation of $f(a, L(a))$ allows for deriving the effect of an increase of learning by doing $L(a)$ on the optimal abatement in period one (a^*). For this, we first take the partial derivative with respect to a and $L(a)$:

$$\begin{aligned} f_a(a, L(a)) &= c_{aa}(a) + \frac{C_L(A, L(a))L_{aa}(a) + C_{LL}(A, L(a))L_a(a)L_a(a)}{1+r} \\ f_{L(a)}(a, L(a)) &= \frac{C_{LL}(A, L(a))L_a(a) + C_L(A, L(a))}{1+r} \end{aligned} \tag{2.4}$$

As $C_{LL} = 0$ holds, we can simplify the derivatives in equation 2.4 to

$$\begin{aligned} f_a(a, L(a)) &= c_{aa}(a) + \frac{C_L(A, L(a))L_{aa}(a)}{1+r} \\ f_{L(a)}(a, L(a)) &= \frac{C_L(A, L(a))}{1+r} \end{aligned} \tag{2.5}$$

Implicit differentiation yields:

$$\begin{aligned} f_a + f_{L(a)}\frac{dL(a)}{da} &= 0 \\ \frac{da}{dL(a)} &= -\frac{f_{L(a)}}{f_a} \\ &= -\frac{C_L(A, L(a))}{(1+r)c_{aa}(a) + C_L(A, L(a))L_{aa}(a)} \\ &> 0 \end{aligned} \tag{2.6}$$

By assumption $c_{aa} > 0$, $C_L < 0$ and $L_{aa} < 0$. The fraction is positive; i.e., a marginal increase of learning by doing leads to an increase of period-one abatement under a carbon tax. Stronger learning by doing reduces future costs. The firm takes this effect into account and increases its abatement early on to benefit from it.

In a carbon tax regime, the choice of abatement in period two A^* is independent of the optimal level of a^*. We can determine the effect of learning by doing on period-two abatement using the total differential of $g(A, L(a))$ defined in equation 2.3. The derivatives of the individual variables are

$$\begin{aligned} g_A(A, L(a)) &= \frac{C_{AA}(A, L(a))}{1+r} \\ g_{L(a)}(A, L(a)) &= \frac{C_{AL}(A, L(a))}{1+r} \end{aligned} \tag{2.7}$$

The total differential yields

$$\begin{aligned} g_A dA^* + g_{L(a)} dL &= 0 \\ \frac{dA^*}{dL} &= -\frac{g_{L(a)}}{g_A} \\ &= -\frac{C_{AL}(A, L(a))}{C_{AA}(A, L(a))} \\ &> 0 \end{aligned} \tag{2.8}$$

As $C_{AA} > 0$ and $C_{AL} < 0$, the total differential is positive. Because more learning by doing leads to higher period-one abatement a^*, the marginal cost decrease in period two is more pronounced. In consequence. the firm chooses a higher abatement level A^* given a fixed carbon tax T.

Proposition 2.2.1. *Under a carbon tax, firms increase their abatement levels in both periods in response to a marginal increase of learning by doing in proximity to the optimum.*

Figure 2.1 illustrates how firms choose higher abatement levels in both periods under a carbon tax as marginal abatement costs curves shift downwards.[6] The new optimal abatement levels $a^*(L_{high})$ and $A^*(L_{high})$ are independent of each other.

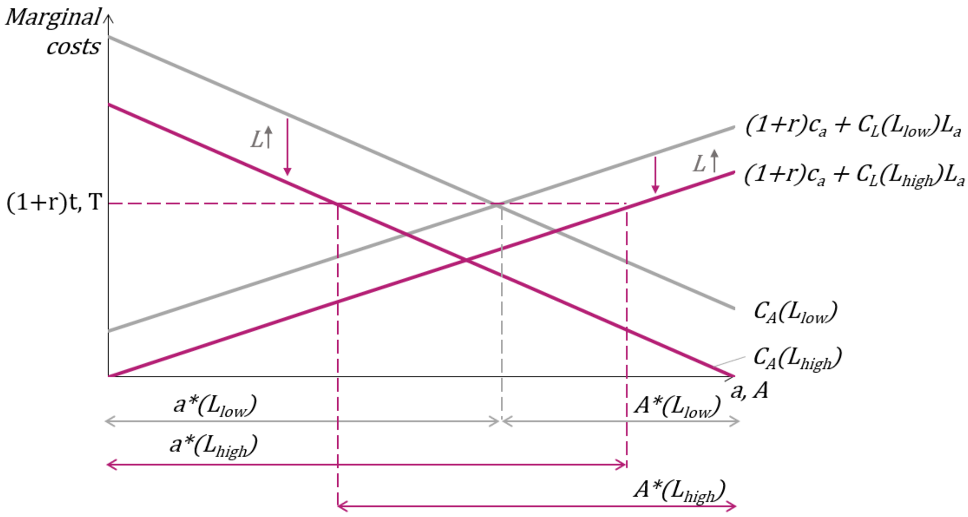

Figure 2.1.: Illustration of the effect of an increase of learning by doing under a carbon tax

2.2.2. Emission trading system

Under an emission trading system, the firms' cost minimization rationale stated in equations 2.1 to 2.3 still holds. However, while a fixed tax affects each firm separately, an ETS creates a market that works under two conditions presented in equations 2.9 and 2.11.

The model represents an idealized ETS without restrictions on banking or borrowing of allowances that covers N firms i ∈ [1,...,N]. The total amount of abatement cannot be lower than $\tilde{A}$, reflecting the intertemporal cap of an emission trading system, i.e.

$$\begin{aligned} &\Sigma_{i=1}^{N}(a_i + A_i) \geq \tilde{A} \\ &\quad \text{with } \tilde{A} \in [0; 2\Sigma_{i=1}^{N} u_i] \end{aligned} \tag{2.9}$$

[6]Note that all figures presented in this research are simplified illustrations. They depict linear curves. The analytical model does not define their functional form apart from the assumptions outlined in section 2.2. Moreover, the propositions in this research hold locally around the initial optimum but not necessarily globally.

must hold.[7] In a cost-minimization setup we can assume that the constraint is binding, such that equality holds. The market clearing condition is then given by

$$\Sigma_{i=1}^{N} A_i(a_i) = \tilde{A} - \Sigma_{i=1}^{N} a_i. \tag{2.10}$$

In contrast to a carbon tax, ETS allowance prices $z = p$ and $Z = P$ are intertemporally connected; i.e., the price in one period influences the price level in other periods. In the analytical model of a simple ETS the price increases with the interest rate according to the Hotelling price path of resource extraction (Rubin, 1996):

$$p = \frac{P}{1+r} \tag{2.11}$$

Emission trading allows for arbitrage. The possibility to buy and sell allowances on a competitive carbon market ensures a result in which firms are indifferent between investing in abatement and investing on the capital market.

In combination with the first-order conditions in 2.2 and 2.3, this yields:

$$c_a(a) = \frac{C_A(A(a), L(a)) - C_L(A(a), L(a))L_a(a)}{1+r} \tag{2.12}$$

for firm-level optimization. In equilibrium, every firm balances the marginal abatement costs of period one with the discounted MAC of period two minus the cost reduction through learning by doing. For determining period-one abatement levels a, the firm takes into account the future benefit from early abatement through learning by doing in terms of lower future costs, $\frac{C_L(A(a),L(a))L_a(a)}{1+r} < 0$. Analogously to a carbon tax, the firm thus chooses a higher abatement level in period one than it would without learning by doing.

Figure 2.2 illustrates the effect for an exogenous cost reduction in period two CR_{exo} that is independent of the previous abatement undertaken by the firm (A.1 analyzes this case in detail). Let us for purpose of illustration assume the firms are identical. From equation 2.10 we can derive that $\frac{\tilde{A}}{N} = a^* + A^* \; \forall i \in [i, ..., N]$. The intersection of the grey curves represents a firm's intertemporal optimum under an ETS with the dashed line showing the distribution of abatement efforts between the two periods, $a^*(CR_{exo})$ and $A^*(CR_{exo})$. With learning by doing, the firm's optimization rationale in period one changes to the blue curve which includes the period-two cost reduction induced by the own period-one abatement efforts. This increases the optimal period-one abatement to $a^*(L)$ and, in consequence, lowers period-two abatement to $A^*(L)$, as a^* and A^* add up to the cap $\tilde{A}$.

While under a carbon tax the firm adjusts marginal abatement costs and induced learning by doing to a fixed tax level t, the firm balances the costs of two periods under an ETS. Consequently, it is not possible to state under which

[7] Given constant baseline emissions u, a minimum amount of required abatement is equivalent to a cap on total emissions.

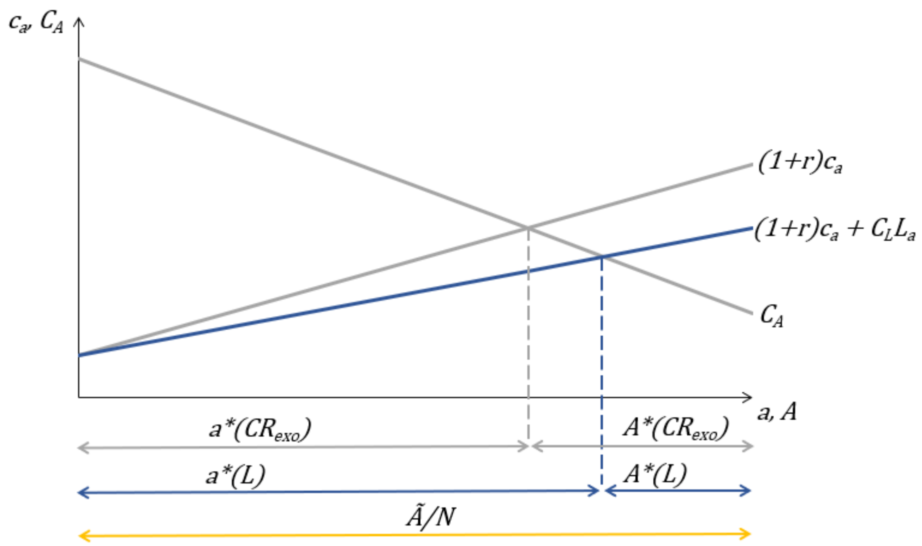

Figure 2.2.: Comparison of equilibrium abatement under an exogenous cost reduction and learning by doing

carbon pricing regime the firm chooses a higher period-one abatement level a^* as this depends on the level of the carbon tax t in this period.

We can apply total differentiation to the market clearing condition (2.10). Again assuming identical firms, we derive $\partial A(a)/\partial a = -1$ locally at the equilibrium a^*. This allows us to rewrite the firm-level optimization as a function $h(a, L(a))$ with

$$h(a, L(a)) \coloneqq c_a(a) + \frac{C_a(a, L(a)) + C_L(a, L(a))L_a(a)}{1+r} = 0. \tag{2.13}$$

Implicit differentiation allows deriving the effect of an increase of learning by doing $L(a)$ on the optimal abatement in period one (a^*). For this, we first take the partial derivative with respect to a and $L(a)$.

$$\begin{aligned} h_a(a, L(a)) &= c_{aa}(a) + \frac{1}{1+r}[C_{aa}(a, L(a)) + 2C_{aL}(a, L(a))L_a(a) \\ &\quad + C_L(a, L(a))L_{aa}(a) + C_{LL}(a, L(a))L_a(a)L_a(a)] \\ h_{L(a)}(a, L(a)) &= \frac{C_{aL}(a, L(a)) + C_{LL}(a, L(a))L_a(a) + C_L(a, L(a))}{1+r} \end{aligned} \tag{2.14}$$

As $C_{LL} = 0$ holds, we can simplify the derivatives to

$$\begin{aligned} h_a(a, L(a)) &= c_{aa}(a) + \frac{C_{aa}(a, L(a)) + 2C_{aL}(a, L(a))L_a(a) + C_L(a, L(a))L_{aa}(a)}{1+r} \\ h_{L(a)}(a, L(a)) &= \frac{C_{aL}(a, L(a)) + C_L(a, L(a))}{1+r} \end{aligned} \tag{2.15}$$

Analogously to the approach in equation 2.6, implicit differentiation yields

$$\begin{aligned} h_a + h_{L(a)} \frac{dL}{da^*} &= 0 \\ \frac{da^*}{dL} &= -\frac{h_{L(a)}}{h_a} \\ &= -\frac{C_{aL}(a, L(a)) + C_L(a, L(a))}{(1+r)c_{aa}(a) + C_{aa}(a, L(a)) + 2C_{aL}(a, L(a))L_a(a) + C_L(a, L(a))L_{aa}(a)} \end{aligned}$$

Note that equation 2.10 implies that $C_{aa} = C_{AA}$ and $C_{aL} = -C_{AL}$.

We can rewrite the fraction to

$$\begin{aligned} &= \frac{C_{AL}(A, L(a)) - C_L(A, L(a))}{(1+r)c_{aa}(a) + C_{AA}(a, L(a)) - 2C_{AL}(a, L(a))L_a(a) + C_L(A, L(a))L_{aa}(a)} \\ &\lesseqgtr 0 \end{aligned} \tag{2.16}$$

By assumption c_{aa}, C_{AA}, $L_a > 0$ and C_L, C_{AL}, $L_{aa} < 0$. Thus, the denominator of the fraction is positive. The numerator consists of a positive term, $-C_L$, and a negative term, C_{AL}, and can hence be either positive or negative. Learning by doing causes two opposing effects in emission trading systems. On the one hand, learning by doing incentivizes early abatement as more abatement in period one reduces abatement costs for all abatement options in period two (*learning effect*, C_L). On the other hand, a cost reduction in period two makes it rational to postpone abatement in a Hotelling environment with an emission cap (*Hotelling effect*, C_{AL}).[8]

Proposition 2.2.2. *If $|C_L| > |C_{AL}|$, the learning effect is stronger than the Hotelling effect and abatement efforts are frontloaded in response to a marginal increase of learning by doing in an ETS with identical firms in proximity to the optimum. Otherwise, abatement is postponed.*

Under a carbon tax, only the *learning effect* occurs as equation 2.6 shows. The *Hotelling effect* does not occur because the choice of period-two abatement

[8] A.1 shows that this effect also occurs with an exogenous cost reduction. Firms postpone abatement if they expect future abatement costs to decrease.

A^* solely depends on its marginal abatement costs C_A and do not need to be balanced with the marginal abatement costs of period one c_a.

The intuition behind ambiguous effect of learning by doing on the intertemporal distribution of abatement under an ETS is that the two identified effects act on two different levels. The *learning effect* C_L acts on the total cost level. Learning by doing reduces costs of all abatement options along the MAC curve. In contrast, the *Hotelling effect* C_{AL} works at the marginal abatement cost level. It shifts the equilibrium of marginal abatement costs between the two periods. The effect that is stronger determines the direction of the total effect of learning by doing. While both effects are interconnected, it is not possible to make a clear statement on which effect is dominant. This depends on the actual functional form of the abatement costs in period two.

Figure 2.3 illustrates this. The grey curves represent the initial equilibrium with a low level of learning by doing L_{low}. The equilibrium forms according to equation 2.12 at the point at which $C_A(L_{low})$ equals $(1+r)c_a + C_L(L_{low})L_a$. The dashed line shows how the ETS cap $\tilde{A}$ is distributed between the two periods with equilibrium period-one abatement level $a^*(L_{low})$ and period-two abatement level $A^*(L_{low})$. If learning by doing increases to L_{high}, the distribution of abatement might lead to more abatement early on in period one or later in period two. The blue curves illustrate the first case. The increased learning has a stronger effect on C than on C_A. The *learning effect* dominates the *Hotelling effect* and frontloads abatement; i.e., the equilibrium abatement level in period one increases from $a^*(L_{low})$ to $a^{F*}(L_{high})$ and period-two abatement decreases from $A^*(L_{low})$ to $A^{F*}(L_{high})$. If, however, the effect of learning by doing on C_A is stronger, as depicted by the magenta curve, the equilibrium abatement level in period one decreases from $a^*(L_{low})$ to $a^{P*}(L_{high})$ and period-two abatement increases from $A^*(L_{low})$ to $A^{P*}(L_{high})$. In this scenario, abatement efforts are postponed as the *Hotelling effect* dominates the *learning effect*.

The interplay of both effects lead to ambiguous results in Goulder and Mathai (2000) and Nachtigall and Rübbelke (2016). Goulder and Mathai (2000) model the welfare-optimal distribution of abatement over time. As ETS yield the social optimum in simple models (Cronshaw and Kruse, 1996), it is not surprising that the effect of learning by doing is the same in both set-ups. While Nachtigall and Rübbelke (2016) analyze a setting with a carbon tax, they model the extraction of a finite fossil resource which has the effect of an emissions cap (Rubin, 1996).

Note that, as an ETS sets a fixed cap (expressed in equation 2.9), any increase in a^* results in a 1:1 decrease in A^*. In contrast, learning by doing increases abatement efforts in both periods under a carbon tax as section 2.2.1 showed.

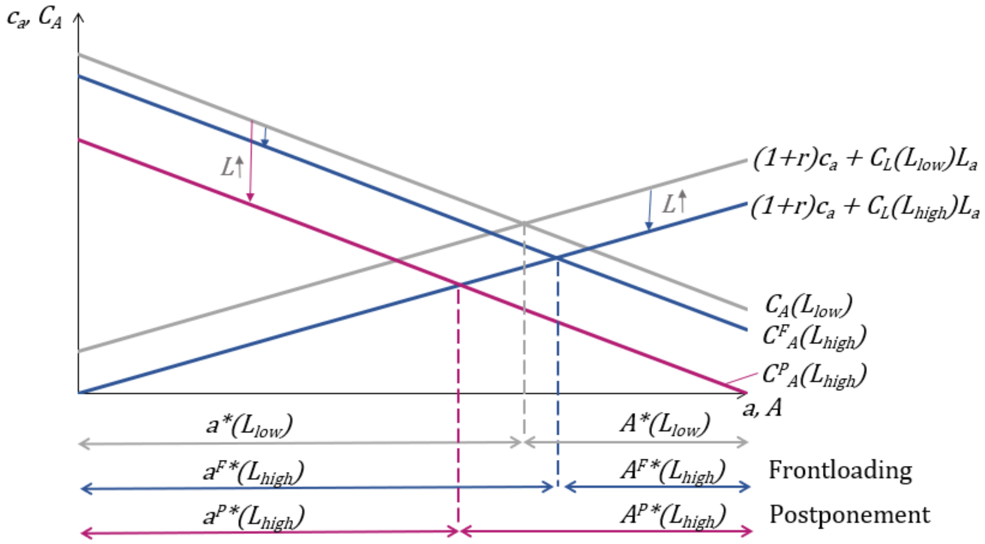

Figure 2.3.: Illustration of the ambiguous effect of an increase of learning by doing

2.3. Total costs under learning by doing

In the previous section, we analyzed the marginal effect of learning by doing on abatement levels and the distribution of abatement between the two periods. We compared the dynamics of both carbon pricing regimes but were not able to make statements on the quality of both regimes in comparison. For this, let us introduce a benevolent regulator that aims to reduce emissions either through a carbon tax or an ETS. To ensure regulatory certainty for firms, the regulator needs to commit to her choice before the two abatement periods. The regulator balances costs of abatement and damage from pollution. The damage function is convex without thresholds and, in contrast to Weitzman (2020), the timing of abatement does not matter for the damage. For an ETS (denoted by index E), the regulator sets the target abatement level $\tilde{A}$ such that marginal damage of emissions equals expected marginal abatement costs including the cost reduction through learning by doing. For a carbon tax (denoted by index X), she sets the tax rate at the level of the marginal damage and hence at the ETS allowance price level. The analysis differs from the model in Weitzman (2020) in which the regulator chooses ex ante different target abatement levels under both regimes as a result of the two independent damage functions in both periods. In the model at hand, the expected outcome in terms of abatement levels in both periods is identical under both regimes. Realized outcomes however differ as there is an information asymmetry between the regulator and the firms regarding the level of learning by doing L. The firms have private information on the technological development and hence know the level of learning by doing better than the regulator.[9] This section aims to understand how an under-/overestimation of learning effects by the regulator affects the costs and abatement levels of the firms.

If the actual level of learning by doing is higher (lower) than the expected level $E[L]$, the abatement level under an ETS does not change as it is fixed to $\tilde{A}$. Section 2.2.1 showed that under a fixed carbon tax of t and T firms choose higher (lower) abatement levels a_X^* and A_X^* in both periods compared to the expected levels $E[a]$ and $E[A]$. In consequence, the total abatement level under a tax is higher (lower) than under an ETS. Figure 2.4 illustrates this for the case in which learning by doing is stronger than expected by the regulator.

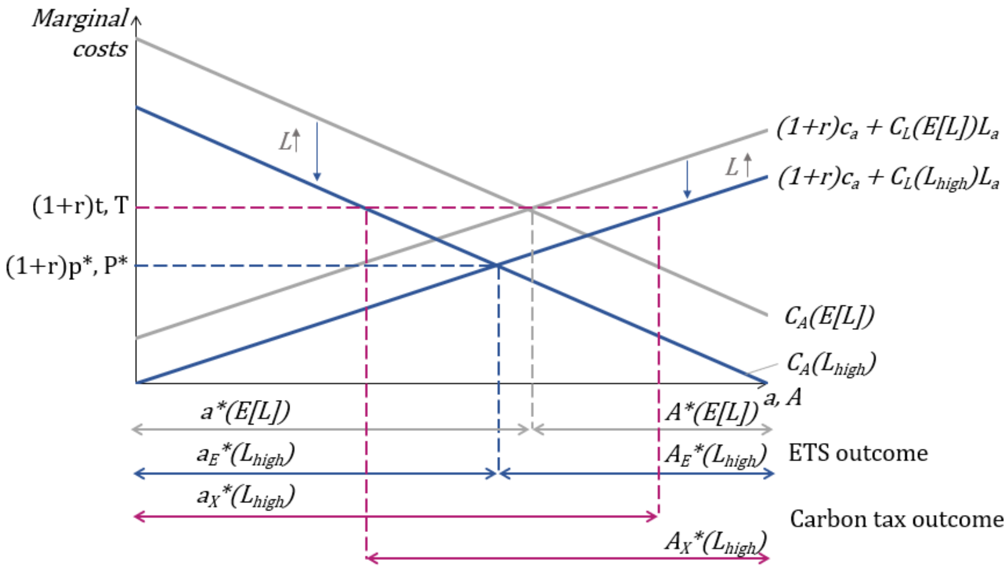

Figure 2.4.: Comparison of tax and ETS if learning by doing is stronger than expected by the regulator

The grey curves represents the regulator's expectation. The expected equilibrium defines the tax levels t and T. If learning is stronger than expected, marginal abatement cost curves mac and MAC, derived from the first-order conditions from equations 2.2 and 2.3, shift downward in both periods as

$$mac_L = C_{LL}(A(*), L(a))L_a(a) + C_L L_{aa} = C_L(A(*), L(a)) < 0 \tag{2.17}$$

and

$$MAC_L = C_{AL}(A(*), L(a)) < 0 \tag{2.18}$$

[9]This research analyzes asymmetric information instead of uncertainty, i.e., a situation in which firms learn the actual costs over time. Note that in a Weitzman (1974) setting with one period uncertainty and asymmetric information are equivalent: The regulator takes her decision without knowing abatement costs, and firms choose their abatement based on actual costs. It is irrelevant if firms knew the actual costs from the beginning (reflecting asymmetric information) or learned it over time (reflecting uncertainty).

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The resulting equilibrium (intersection of blue curves) leads to lower allowance prices p^* and P^* in an ETS. The fixed tax levels, in turn, lead to a choice of higher abatement levels by the firms (dashed magenta lines).[10]

To compare total costs under both carbon pricing regimes in the case of stronger learning by doing, let us set up a benchmark case (denoted by index $B1$) in which firms are regulated under an ETS but choose the period-one abatement level equal to the one they would choose under a carbon tax, i.e., $a^*_{B1} := a^*_X$. Costs occurring in period one and the level of learning by doing under the benchmark and a tax regime are hence the same. The market price of allowances is determined by marginal abatement costs and hence $p^*_{B1} = t$. As the regulatory setup is an ETS, period-two abatement is defined by the cap, i.e., $A^*_{B1} = \tilde{A} - a^*_{B1}$. We know from section 2.2.1 that abatement levels under a tax increase in response to a marginal increase of learning by doing. As the total level of abatement does not change under an ETS, $A^*_X > A^*_{B1}$ holds, and $C(A^*_X, L_{high}(a^*_X)) > C(A^*_{B1}, L_{high}(a^*_X))$ as $C_A > 0$. As learning by doing is stronger than expected and equation 2.18 holds, $T > P_{B1}$. Hence, total costs of the tax exceed those of the benchmark case:

$$\begin{aligned}
TC_X(a^*_X, A^*_X, &L_{high}(a^*_X)) \\
&= c(a^*_X) + t(u - a^*_X) + \frac{C(A^*_X, L_{high}(a^*_X)) + T(u - A^*_X)}{1+r} \\
&> c(a^*_X) + p_{B1}(u - a^*_X) + \frac{C(A^*_{B1}, L_{high}(a^*_X)) + P_{B1}(u - A^*_{B1})}{1+r} \\
&= TC_{B1}(a^*_X, A^*_{B1}, L_{high}(a^*_X))
\end{aligned} \tag{2.19}$$

In turn, cost-effective intertemporal distribution of abatement under the ETS outperforms the benchmark:

$$\begin{aligned}
TC_{B1}(a^*_X, A^*_{B1}, &L_{high}(a^*_X)) \\
&= c(a^*_X) + p_{B1}(u - a^*_X) + \frac{C(A^*_{B1}, L_{high}(a^*_X)) + P_{B1}(u - A^*_{B1})}{1+r} \\
&> c(a^*_E) + p^*(u - a^*_E) + \frac{C(A^*_E, L(a^*_X)) + P^*(u - A^*_{B1})}{1+r} \\
&= TC_E(a^*_E, A^*_E, L_{high}(a^*_E))
\end{aligned} \tag{2.20}$$

[10] To simplify the illustration, the graph depicts identically shifted curves under a tax and an ETS. In the model, the curves shift differently as period-one abatement levels a^*_X and a^*_E and in consequence the induced level of learning by doing differ.

In consequence, total costs for firms under an ETS are lower than under a carbon tax if learning by doing is stronger than expected, i.e,

$$TC_X(a_X^*, A_X^*, L_{high}(a_X^*)) > TC_E(a_E^*, A_E^*, L_{high}(a_E^*)). \tag{2.21}$$

For the case in which learning by doing is weaker than expected we require a different benchmark case (denoted by index $B2$). For this, let us assume firms are regulated under a carbon tax but choose the equilibrium abatement levels as under an ETS, i.e, $a_{B2}^* := a_E^*$ and $A_{B2}^* := A_E^*$. The level of learning by doing and in consequence the marginal abatement costs are identical in the benchmark and the ETS case. If learning by doing is lower than expected, equations 2.17 and 2.18 show that equilibrium ETS price levels p^* and P^* are higher than the tax levels t and T that are set ex ante by the regulator based on higher expected learning by doing. Therefore, total costs under an ETS are higher than under the benchmark:

$$\begin{aligned} TC_E(a_E^*, A_E^*, L_{low}(a_E^*)) &= c(a_E^*) + p^*(u - a_E^*) + \frac{C(A_E^*, L_{low}(a_E^*)) + P^*(u - A_E^*)}{1+r} \\ &> c(a_E^*) + t(u - a_E^*) + \frac{C(A_E^*, L_{low}(a_E^*)) + T(u - A_E^*)}{1+r} \\ &= TC_{B2}(a_E^*, A_E^*, L_{low}(a_E^*)) \end{aligned} \tag{2.22}$$

In this benchmark, marginal abatement costs are above the tax rates in both periods. Firms could reduce their total costs by abating less and, hence, total costs in the benchmark are higher than under the carbon tax:

$$\begin{aligned} TC_{B2}(a_E^*, A_E^*, L_{low}(a_E^*)) &= c(a_E^*) + t(u - a_E^*) + \frac{C(A_E^*, L_{low}(a_E^*)) + T(u - A_E^*)}{1+r} \\ &> c(a_X^*) + t(u - a_X^*) + \frac{C(A_X^*, L_{low}(a_X^*)) + T(u - A_X^*)}{1+r} \\ &= TC_X(a_X^*, A_X^*, L_{low}(a_X^*)) \end{aligned} \tag{2.23}$$

We can hence conclude that total costs under a carbon tax are lower than under an ETS if learning by doing is weaker than expected by the regulator, i.e.,

$$TC_X(a_X^*, A_X^*, L_{low}(a_X^*)) < TC_E(a_E^*, A_E^*, L_{low}(a_E^*)). \tag{2.24}$$

This analysis shows that

Proposition 2.3.1. *In case of asymmetric information between regulator and firms on the strength of learning by doing, a carbon tax yields lower total costs than emission trading if the regulator overestimates learning by doing in proximity to the true optimum and vice versa in the case of an underestimation.*

Without knowing the functional form of learning by doing, the regulator cannot prefer one carbon pricing regime over the other in terms of minimizing total costs. While committing to a carbon tax induces higher costs than those under an ETS in case of stronger learning by doing than expected, a fixed abatement level under an ETS leads to inefficiently high abatement if the level of learning by doing is lower. The analysis indicates that firms might have an incentive to reveal their expected level of learning by doing to the regulator, such that she can target an optimal carbon price ex ante. The case of asymmetric information on learning by doing is comparable to asymmetric information on any other cost components. Hence the results are consistent with the findings in D'Amato and Dijkstra (2015) and Requate and Unold (2003) who compare the two carbon pricing regimes in a setting with asymmetric information on technology adoption costs. Requate and Unold (2003) conclude that a carbon tax outperforms an ETS in terms of abatement levels in a case in which the regulator does not anticipate the development of a new low-carbon technology. This is equivalent to the case in which learning by doing is stronger than expected. The analysis at hand, in turn, draws attention to a situation in which the regulator overestimates learning by doing or technological development in general. In this case an ETS leads to higher abatement levels and total costs than a carbon tax.

2.4. Conclusion

Currently, abatement costs for deep decarbonization are high and technologies are not yet fully developed to reach climate neutrality without losses in living standard. For an efficient abatement path towards climate neutrality, we need a deep understanding of the dynamics of climate policy instruments. In particular, it is essential to comprehend how learning can be encouraged and in general how abatement technologies evolve and innovations are triggered. The research at hand adds to our knowledge by analyzing the effects of learning by doing in carbon pricing regimes.

Section 2.2 shows that under a carbon tax, learning by doing leads to more experience being gathered early on in order to enable cost reductions. In contrast, the effect is ambiguous under an emission trading system. More learning can lead to either a frontloading or a postponement of abatement efforts. The ambiguity is a result of two opposing effects induced by learning by doing: a *learning effect* and a *Hotelling effect*. The analysis illustrates that it is not possible to state which of the two effects is dominant in an ETS without knowing the concrete abatement cost function of period two. Intuitively, one can argue that the more ambitious an ETS cap is, the higher the initial period-two abatement level that benefits from increased learning by doing and the more likely the *learning effect* dominates the *Hotelling effect* and hence frontloading abatement efforts is optimal. Further theoretical and empirical research is needed to understand real-life abatement costs and learning behavior.

Note that section 2.2 does not evaluate the welfare effects of the identified dynamics in both carbon pricing regimes. In particular, the postponement of abatement in itself is not an undesired feature of intertemporal climate policy. If costs are expected to decrease, it is optimal to wait.

Section 2.3 extends the analysis to a comparison of total costs under a carbon tax and an ETS in a setting with asymmetric information on the actual level of learning by doing. If learning by doing is stronger than expected by the regulator, total costs are lower under an ETS. If it is weaker than expected, firms prefer a carbon tax. The analysis highlights the importance of learning by doing for the outcome of carbon pricing. In particular, if the regulator ignores learning by doing, she will set a target abatement level that is too low because she will assume that marginal abatement costs are higher than they are with learning by doing. It is recommendable for the regulator to understand learning by doing and acquire empirical data in order to close the information gap between firms and regulator.

The research emphasizes that the intertemporal nature of emission trading systems has, compared to a static carbon tax, complex side effects that require further research. One worthwhile extension of this research would be to analyze the interaction between learning by doing and complementary policies like overlapping national measures or carbon price floors. Another extension could be to explore the role of the rational formation of expectations under an ETS regarding the effect of learning by doing.

3. The reformed EU ETS - Intertemporal emission trading with restricted banking

3.1. Introduction

In 2005, the European Union Emissions Trading System (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.[11] This restriction may create short-run scarcity in the market, leading to a deviation from the original Hotelling price path. Chevallier (2012) applies

[11] 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.

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).[12]

Recent contributions by Richstein et al. (2015), Perino and Willner (2016) and Beck and Kruse-Andersen (2018) 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 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

[12]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).

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 (2018) 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.[13] 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 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.

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

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 $t = 0, 1, \ldots, T$ 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 $e(t)$.[14]

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

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

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.[15] 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 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 $a(t)$,

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

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

hence $S(t) = S(t-1) - a(t)S_0$.[16] The issued allowances are partially auctioned ($S_{auct}(t)$) and partially distributed for free.[17]

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.[18] 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 $\tau_{b=0}$.[19]

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.

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

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

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

[18] 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.

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

inserted into the MSR. If $TNAC(t)$ drops below a lower limit ℓ_{low}, R allowances from the MSR are auctioned additionally.[20]

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 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.

[20] 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).

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 (2018). 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.[21]

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, 2018), 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).[22]

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[23], 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 $C'(0) = \bar{c}$.

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.

[21] 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)

[22] 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.

[23] 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)).

3.3.1. 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)[24] and remains at this upper limit. This happens from 2058 onwards.

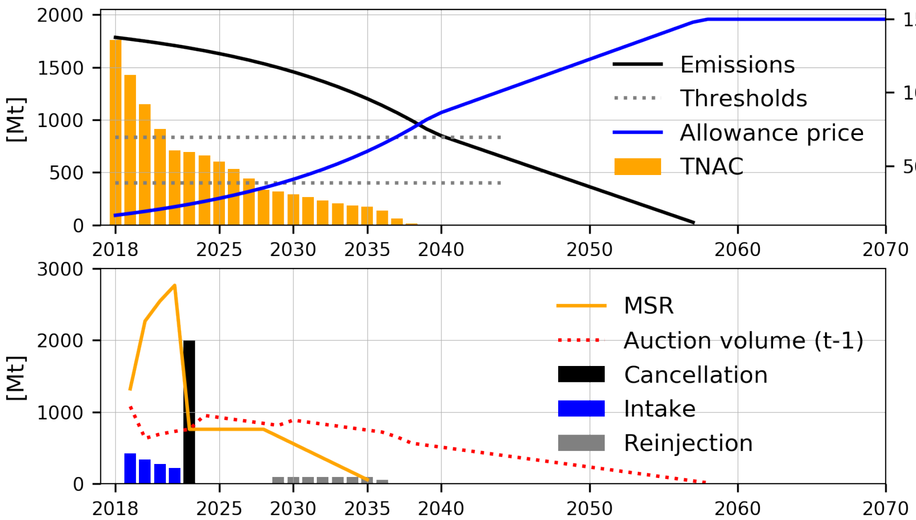


Figure 3.1.: Development of emissions, TNAC, MSR, cancellation and allowance prices

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.[25] This is equivalent to about 5%

[24]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.

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

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 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.

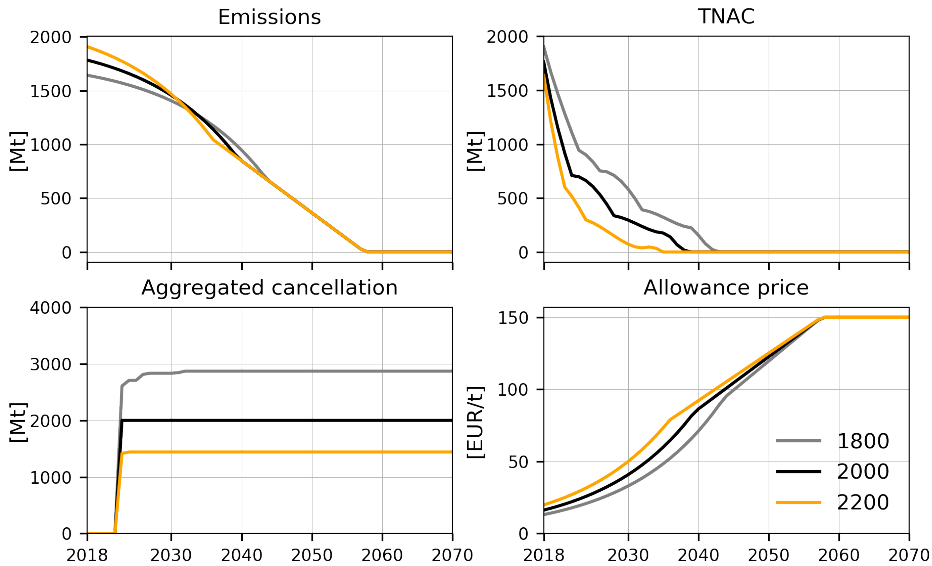


Figure 3.2.: Sensitivity analysis for baseline emissions

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.

Over time declining baseline emissions (as assumed by, e.g., Carlén et al. (2018) and Quemin and Trotignon (2019b)) 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.

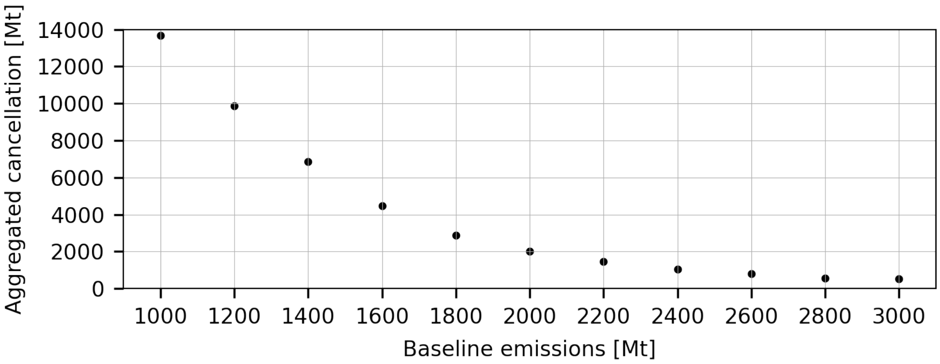


Figure 3.3.: Effect of baseline emissions on cancellation

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.[26]

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

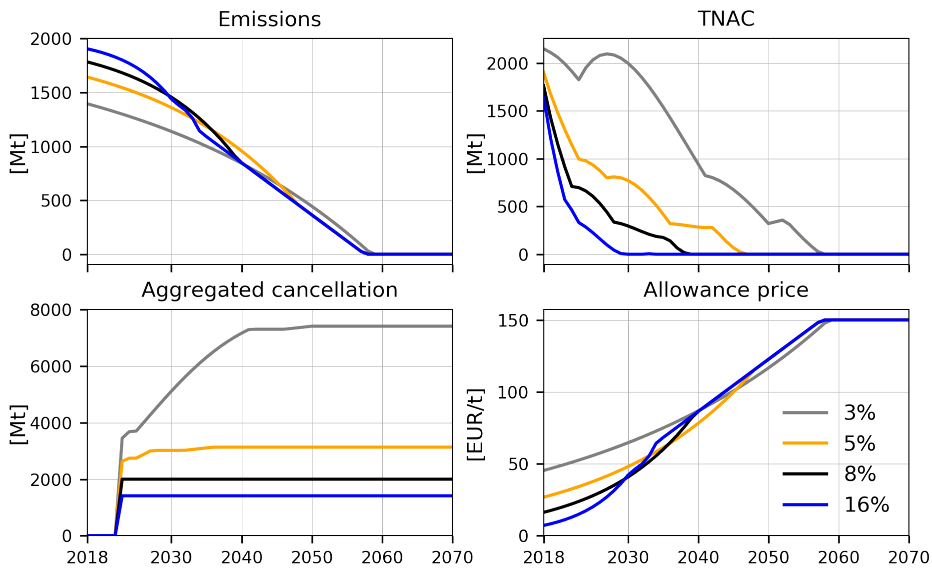


Figure 3.4.: Sensitivity analysis for the interest rate

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.

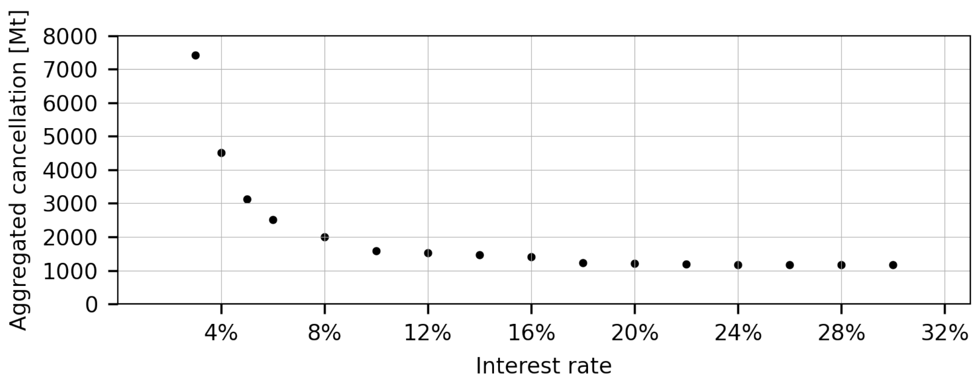


Figure 3.5.: Effect of interest rate on cancellation

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 (2018) 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, 2018). 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. [27] 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 (2018) 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.[28] 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.

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

[28] 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 Carlén et al. (2018) and Perino and Willner (2017). With their iterative solution approach, Carlén 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.

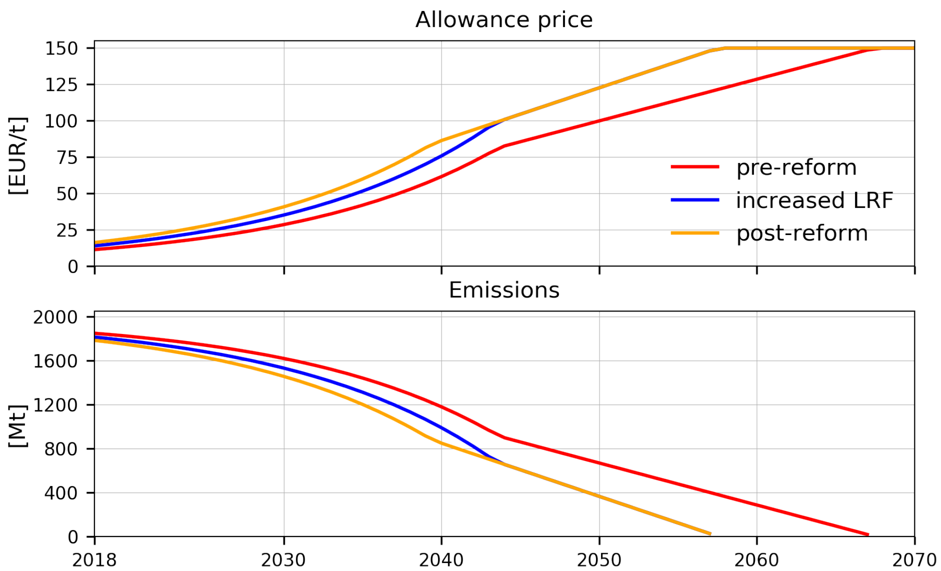


Figure 3.6.: Effect of the change in the LRF

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).

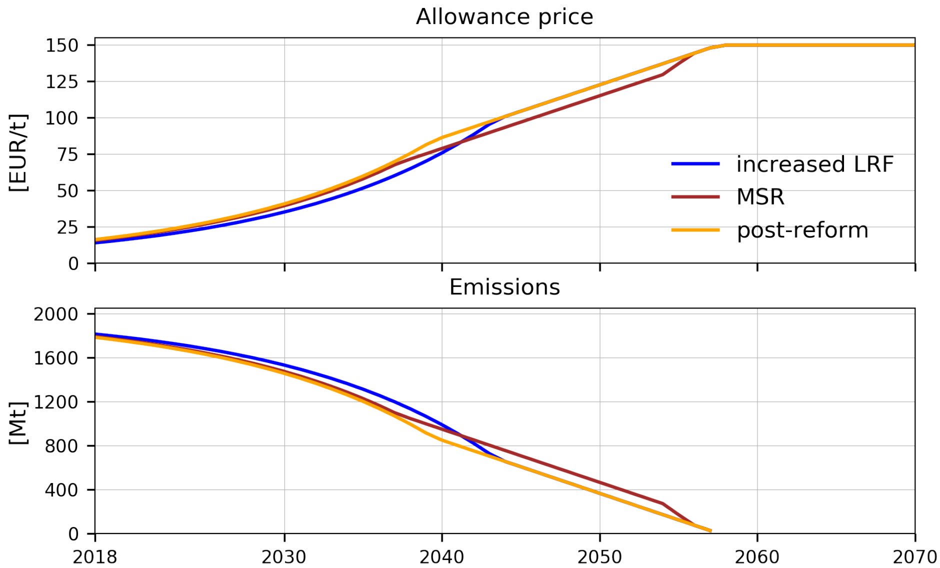


Figure 3.7.: Effect of the MSR and the CM

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 $\tau_{b=0}$.[29] 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.

[29]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.[30] 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. [31]

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.[32]

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.

[30]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%.

[31]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)).

[32]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)).

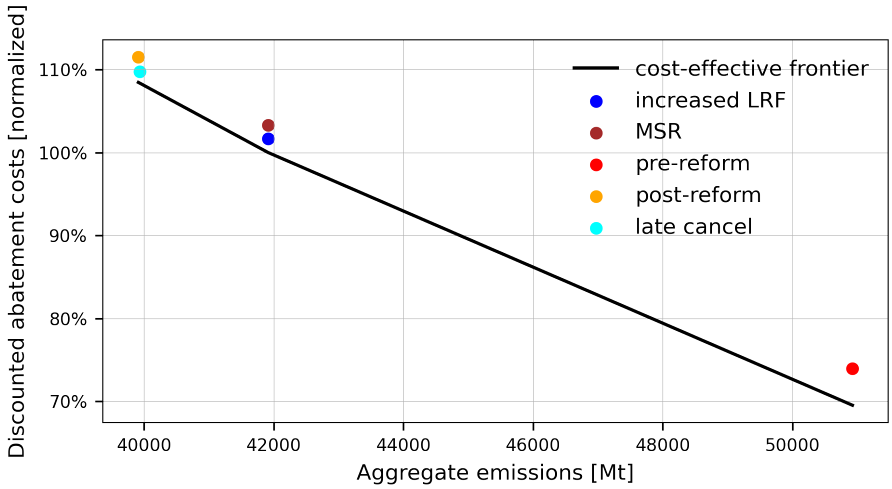


Figure 3.8.: Comparison of discounted abatement costs and emission levels in different scenarios

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.[33] 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 path, but does not further impact the resulting quantities. Baseline emissions in

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

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. Fit for 55? An assessment of the effectiveness of the EU COM's reform proposal for the EU ETS

4.1. Introduction

Since its establishment in 2005, the European Union Emissions Trading System (EU ETS) has been reformed multiple times, changing its underlying incentive structure. The reformed and strengthened EU ETS currently reaches price levels of about 90 Euro per EU allowance (EUA) in February 2022, compared to an average of 24.9 Euro in 2020 and 5.8 Euro in 2017 (ICE, 2022). While other factors may influence EUA prices, the EU ETS experienced a significant price increase after its latest reform in 2018. Similarly, the EUA price increased after the European Commission (EU COM) announced its 'Fit for 55' legislative package in July 2021 that proposes measures to achieve the increased EU climate targets to at least 55% reduction until 2030 compared to 1990 levels and climate neutrality until 2050 set in the European Climate Law (European Parliament and the Council of the European Union, 2021). The 'Fit for 55' package contains a substantive reform proposal for the EU ETS with three key reform elements that aim at strengthening the existing EU ETS: an increase of the linear reduction factor (LRF), an adjustment of the intake rules of the Market Stability Reserve (MSR) and an adjustment of the threshold for the Cancellation Mechanism (CM) (European Commission, 2021e).

The first element, the increase of the LRF, i.e., the rate at which the EU ETS cap decreases each year, aims at achieving the new, more ambitious climate target of at least 55% reduction until 2030. In accordance with the impact assessment for the 'Fit-for-55' package, the EU COM proposes an increase of the LRF to achieve a 61% reduction of EU ETS emissions compared to 2005 (European Commission, 2021b).

In 2015, the EU introduced the MSR with the aim of addressing imbalances of supply and demand of allowances and increasing the market's resilience to shocks (European Commission, 2021d). It adjusts the annual supply of allowances in response of the total number of allowances in circulation (TNAC), transferring excess allowances into a public reserve or reinjecting allowances from the MSR back into the market (European Parliament and the Council of the European Union, 2015). In 2018, the EU complemented the MSR with a CM rendering allowances invalid if the MSR volume exceeds a pre-determined threshold (European Parliament and the Council of the European Union, 2018). It was further established that the EU COM should review the MSR within the first three year after it entered into force in 2019 (European Parliament and the Council of the European Union, 2015).

The second element of the proposed EU ETS reform is the two-fold adjustment of the MSR intake rules. First, an increase of the MSR intake rate is proposed to reduce the number of allowances in the market that potentially cause a surplus of allowances (European Commission, 2021d). Second, a buffer zone shall reduce threshold effects potentially caused by the regulation in place. The aim of the buffer zone is hence to decrease price volatility (European Commission, 2021e). Price volatility is, among others, induced by abrupt shifts in allowance demand or supply that may lead to sudden changes in the EUA price levels.

The third proposed change to the mechanisms of the EU ETS is the adjustment of the CM that limits the amount of allowances in the MSR. The EU COM aims at increasing the predictability of the CM by proposing a fixed threshold for cancellation instead of the currently flexible threshold (European Parliament and the Council of the European Union (2018) and European Commission (2021e)).[34] [35]

The research at hand analyzes the effects of the reform proposal on the price and abatement paths in the EU ETS. In particular, it aims to understand how the reform proposal could have contributed to the price increase and how the relative impact of the individual reform elements on price levels is. A focus of the analysis is on whether the individual reform elements effectively achieve their intended goals: The increase of the LRF aims at achieving the new, more ambitious climate target. The adjustment of the MSR rules with the introduction of a buffer zone and a long-term higher MSR intake rate aims to tackle market imbalances as well as to reduce price volatility in the EU ETS. The proposal for a fixed cancellation threshold targets the predictability of the CM.

For this purpose, the research extends a model of the EU ETS developed in Bocklet et al. (2019) with the latest reform proposal. The discrete-time numerical model optimizes firms' abatement in response to their expectation of the

[34]In addition to the outlined adjustments, the EU COM proposes an extension of the EU ETS to the maritime and aviation sectors into the main EU ETS (European Commission, 2021e). While both sectors only have a limited amount of emissions (the aviation and maritime caps are approx. 24 and resp. 79 million allowances (European Commission (2020) and European Commission (2021e)), the complex provisions for their integration into the EU ETS would impact the market outcome in hard to disentangle ways. For the purpose of clearly decomposing the individual effects of the three reform amendments outlined above, the research refrains from including these provisions.

[35]The EU adopted the reform in April 2023. The adjustments to the MSR and the CM were adopted as proposed by the EU COM. The final LRF is 4.3% from 2024 to 2027 and 4.4% from 2028 (instead of 4.2%) with cap rebasings of 90 million in 2024 and 27 million in 2026 (instead of a single reduction of 117 million allowances in 2024)(European Parliament and the Council of the European Union, 2023). The adopted reform is hence slightly more ambitious that the initial proposal discussed in the article at hand.

allowance price path in the EU ETS. It accurately depicts the EU ETS in its current regulation including the MSR and CM as well as the proposed adjustments. Different scenarios that integrate only one additional reform element help to decompose the aggregate impact of the reform into the effects of the individual reform elements. By comparing the scenarios with and without the individual reform element, the analysis assesses the effectiveness of the element; i.e., whether it achieves its intended goal.

The analysis finds that while the proposed reform achieves a higher predictability of the CM, it does not ensure reaching the new climate target for 2030. Moreover, the impact of the proposed adjustment of the MSR intake on reducing allowance surplus and decreasing price volatility is ambiguous. The model results show how the existing mechanism for MSR intake induces sudden increases or decreases in the allowance supply, thereby potentially destabilizing the EUA price. The introduction of the buffer zone smooths allowance supply as it prevents threshold effects caused by the current regulation. It hence reduced the probability of supply-induced shocks but does not address price variability caused by the MSR. Moreover, it may also reduce MSR intake and cancellation volumes which is in conflict with the other MSR goal of reducing the number of allowances in circulation. In any case, the model results also show that the overall impact of the proposed change in the MSR intake rules may be low.

The analysis of emissions trading systems builds upon the seminal work of Hotelling (1931) on the optimal extraction path of finite resources. Hotelling (1931) shows that, in an ideal setting, extraction adjusts such that gains from extraction develop with the same rate as gains from alternative investments, that is the interest rate of capital. Rubin (1996) is the first to apply this finding to an ETS. His work is fundamental to understand the nature of an ETS based on an intertemporal allocation of an overall emissions budget.

Recently, research using numerical models of the EU ETS emerged that analyzes the dynamics of the regulatory system and draws conclusions on the efficiency and effectiveness of the EU ETS and its different reforms. Richstein et al. (2015) and Perino and Willner (2016) evaluate how the MSR affects price and abatement paths and find that the MSR does not fulfil its intended purpose of increasing market stability. Instead, it increases price variability. Bocklet et al. (2019) and Quemin and Trotignon (2019a) analyze the impact of the Cancellation Mechanism. Beck and Kruse-Andersen (2018) and Schmidt (2020) show that the CM changes the impact of overlapping national policies which can reduce emissions in the reformed EU ETS, if implemented early on. Bocklet (2020) analyzes the impact of crises on the EU ETS and finds that MSR and CM can decrease price volatility in times of crisis.

Osorio et al. (2021) and Pietzcker et al. (2021) analyze the EU ETS in the context of more ambitious EU climate targets. Both articles do not consider the 2021 reform proposal. Pietzcker et al. (2021) assess the impact of a 63% reduction sector of the European power sector and find that coal-fired electricity generation would phase out until 2030. Osorio et al. (2021) analyze market outcomes under a range of MSR parameters (auction share, thresholds and intake rate) and LRF options with a focus on the interactions between both reform elements. They find that an MSR reform can both lead to significantly more or less cancellation and that the increased LRF may lead to up to twice the cancellation volume depending on the applied MSR parameters. In contrast to Bocklet (2020), they find that cancellation volumes are hard to predict which leads to high price uncertainty.

There is so far no scientific analysis of the EU ETS reform proposal within the 'Fit for 55' package. In preparation of the proposal, the EU COM conducted an impact assessment analyzing different options for reforming the MSR and CM (European Commission, 2021b). The impact assessment uses a model developed in Quemin and Trotignon (2019b) that is similar to the model applied in the research at hand. However, the analyzed options differ from the actual EU COM proposal and the combination of different reform elements inhibits developing a clear understanding of which effects can be attributed to which individual reform element. The think tank Sandbag (Sandbag (2021a) and Sandbag (2021b)) has engaged in analyses of the EU ETS reform but use simulation with fixed assumption of emissions levels. The contribution of the research at hand to the existing literature is a comprehensive and transparent analysis of the proposed reform based on most recent data of the EU ETS using 2020 values of TNAC and MSR volume. The research analyzes the overall impact of the proposed reform on abatement and prices as well as the effectiveness of the individual elements. For this, an optimization model of the EU ETS is used to decompose the total impact of the reform into the impact of the individual elements, comparing their effects against their intended aim.

The remainder of this paper is organized as follows: Section 4.2 outlines the content of the current EU ETS reform proposal in detail. Section 4.3 extends the model developed in Bocklet et al. (2019) with the proposal. Section 4.4 introduces scenarios that decompose the impact of the reform into the effects of the individual reform elements and presents the model results. Section 4.5 discusses critical assumptions of the applied model and potential shortcomings of the individual reform elements. Section 4.6 concludes.

4.2. The EU ETS in its current regulation and with the reform proposal

This section explains the EU ETS regulation in detail, contrasting the rules for LRF, MSR and CM in the regulation in place with the EU COM's reform proposal.

4.2.1. Linear reduction factor

The EU ETS cap in its current form applies a LRF of 2.2% meant to achieve an emission reduction of 43% for EU ETS emissions compared to 2005 levels and a 40% climate target for overall emissions in the EU compared to 1990 levels for the year 2030 (European Parliament and the Council of the European Union, 2018). The LRF is not a percentage rate for the cap to decline but rather a share of initial emissions, i.e., a fixed number of allowances, by which the cap decreases each year. For an increased EU climate target of at least 55% reduction until 2030 compared to 1990 levels, the EU COM proposes a 61% reduction of EU ETS emissions compared to 2005, in accordance with the impact assessment for the 'Fit-for-55' package (European Commission, 2021b). This is equivalent to an increase of the linear reduction factor from 2.2% to 4.2% from 2021 onwards (European Commission (2021e)).[36] The EU COM proposes an one-off reduction of 117 million allowances to accommodate the possible timeline of changes to the EU ETS Directive assuming a late implementation in 2024.[37] To achieve the EU's new long-term target of climate neutrality in 2050, the EU ETS needs a LRF of 2.0% from 2031 onward. An extrapolation of the current linear reduction factor of 2.2%, as applied in Bocklet et al. (2019), leads to zero supply of emissions only in 2058.

4.2.2. Market Stability Reserve

In 2015, the EU introduced the MSR with the aim of stabilizing the market by addressing imbalances of supply and demand of allowances and increasing the EU ETS's resilience to shocks (European Commission, 2021d). The MSR started operating in 2019. It adjusts the annual supply of allowances in response of the TNAC volume. If the TNAC is higher than 833 million allowances, the auction volume of a year is reduced by a share of the TNAC. This share is stored in the MSR (European Parliament and the Council of the European Union, 2015). From 2019 to 2023, this share is set to 24%. After 2023, it should decrease to 12% under the current regulation (European Parliament and the Council of the European Union, 2018).

The EU COM proposes a two-fold adjustment of the MSR intake rule. First, draft directive 2021/0202 proposes that the intake rate from 2024 to 2030 should continue to be at 24%. The preamble of the proposal for the directive states that the current intake rate of 12% after 2023 may cause a harmful surplus of allowances. The aim of the increased MSR intake rate is to reduce the number of

[36] In fact, the proposed LRF slightly overachieves the target leading to a emissions reduction of 62% compared to 2005 levels.

[37] European Commission (2021e) leaves the exact value for the one-off reduction option to the year the proposal enters into force but European Commission (2021c) states a reduction of 117 allowances. This, in turn, indicates a target year 2024 for the proposal to enter into force with 39 million allowances for every year from 2021 to 2023 in which the increased LRF is not applied.

allowances in the market. After 2030, the proposal suggests reverting the intake rate from 24% to 12% (European Commission, 2021d). Second, the EU COM identifies a threshold effect caused by the MSR regulation in place: Once the TNAC is at 833 million allowances, MSR intake jumps from zero to 100 (at a 12% intake rate) or 200 million allowances (at a 24% intake rate). The EU COM proposes a smoother intake rule: Within a buffer zone between a TNAC of 833 and 1096 million allowances, only the difference between 833 million allowances and the actual TNAC is transferred to the MSR. At a TNAC of 834 million allowances, that is only one allowance. At a TNAC of 1096 millions allowances, it is 263, which is exactly 24% of the TNAC. In this way, the buffer zone provision reduces MSR intake for a general intake rate of 24%. The aim of the buffer zone is to prevent abrupt spikes in allowance supply, thereby stabilizing EUA prices (European Commission, 2021e).

4.2.3. Cancellation Mechanism

In 2018, Directive 2018/410 introduced a CM rendering allowances in the MSR invalid if the MSR volume exceeds a predetermined threshold. This mechanism endogenizes allowance supply. While the MSR by itself only shifts abatement in time, the CM changes the overall allowance budget available to the market based on the firms' abatement behaviour. The current regulation sets the cancellation threshold to the previous year's auction volume (European Parliament and the Council of the European Union, 2018). In its reform proposal, the EU COM states that the current mechanism is not predictable enough as the cancellation threshold depends on the auction level and in consequence also on the MSR intake as MSR intake reduces the number of allowances that is auctioned. With the proposed reform, the EU COM aims at increasing the predictability of the CM by setting a fixed threshold for cancellation of an MSR volume of 400 million allowances (European Commission, 2021e).

4.3. Modeling the EU ETS reform proposal

To assess the impact of the proposed EU ETS reform, the research extends a numerical optimization model of the EU ETS developed in Bocklet et al. (2019) which is based on the model of an intertemporal allowance market in Rubin (1996). The EU ETS model uses discrete time steps $t = 1, 2, \dots T$ and accurately depicts the EU ETS including the Market Stability Reserve and the Cancellation Mechanism. The updated model compares the 2018 regulation with the EU COM's proposal from July 2021 as described in section 2.

This section sets up the optimization problem of firms in a multi-period emission trading system and derives the market clearing condition. It further sets up model equations for the MSR and CM according to the current regulation and the EU COM's reform proposal. The section concludes with remarks on the model implementation and the applied parameters.

4.3.1. Firms' decision

In the model, N polluting firms have to buy allowances for their emissions and hence decide on their level of abatement $a(t)$ or the number of allowances they buy in each period $x(t)$, respectively. Firms act rationally and have perfect foresight. Extending the original model in Bocklet et al. (2019), Bocklet and Hintermayer (2020) show that hedging of allowances and myopic behavior influenced the EU ETS outcome in the past. While these factors probably continue to play a role in the market behavior, the research at hand refrains from transferring the model results of Bocklet and Hintermayer (2020) to the here applied model for two reasons. First, it is likely that the impact of bounded rationality decreases in market prices and the EU ETS has seen a remarkable increase of prices in the past years (ICE, 2022). With higher stakes in the market, firms should take a longer-term perspective and reduce hedging if it induces additional costs on them. Moreover, the increasing participation of financial actors should likewise have decreased the impact of hedging and myopia. Quemin and Pahle (2021) show that the number of investment funds in the EUA market increased from under 100 in January 2018 to almost 350 in November 2021. Second, the consideration of bounded rationality elements in firms' behavior increases the model complexity at the cost of losing transparency and the ability to disentangle the effects of individual model elements and assumptions. Section 4.5.1 discusses the impact the assumptions of perfect rationality and foresight have on the model results.

Each firm minimizes the present value of its total expenditure which is the sum of abatement costs $C(a(t))$ and payments for $x(t)$ allowances at price $p(t)$ discounted at interest rate r.

$$PV = \sum_{t=0}^{T} \frac{1}{(1+r)^t}[C(a(t)) + p(t)x(t)]. \tag{4.1}$$

The firm can bank the allowances in order to use them at a later point in time. The individual bank of the firm $b(t)$ cannot be lower than zero; that means, a firm cannot emit more than it owns in allowances. The firm has a constant level of baseline emissions u that the firm would have in a hypothetical setup without an emission trading system. Combined with the intertemporal constraint on banking, the minimization problem of the firm is

$$\begin{aligned}
\min_{a(t),x(t)} \quad & \sum_{t=0}^{T} \frac{1}{(1+r)^t}[C(a(t)) + p(t)x(t)] \\
s.t.\ b(t) - b(t-1) &= x(t) - u + a(t) \quad \text{for all} \quad t = 1, 2, \ldots, T \\
b(t) &\geq 0 \\
x(t),\ a(t) &\gtreqless 0.
\end{aligned} \tag{4.2}$$

The Lagrangean optimization yields the equilibrium condition

$$C_a(a(t)) = p(t). \tag{4.3}$$

The firm sets its abatement level $a(t)$ such that the marginal abatement costs equal the allowance price $p(t)$.

The model assumes a marginal abatement cost (MAC) function $C_a(a(t))$ that increases linearly in abatement a_t with an exogenous cost parameter c:

$$C_a(a(t)) = c\, a(t) \tag{4.4}$$

4.3.2. Market equilibrium

The market determines the allowance price such that the demand of the N identical firms and the supply of allowances are in equilibrium. Supply can come from the private bank b_t or the issuance of allowances I_t. The path of issued allowances decreases with a linear reduction factor $\alpha(t)$, i.e. $I(t) = I(t-1) - \alpha(t)I_0$. The regulator issues a share of allowances through auctions $I_{auct}(t)$ and the remaining allowances for free.

It must hold that aggregated emissions, that is baseline emissions minus abatement, over time are smaller than aggregated issued allowances plus the initial bank:

$$\sum_{\tilde{t}=0}^{t}[u - a(\tilde{t})] \leq \sum_{\tilde{t}=0}^{t} I(\tilde{t}) + b_0 \text{ for all } t = 0, 1, \ldots, T. \tag{4.5}$$

The allowance price develops over time according to the following rule, derived from the firm's optimization problem in equation 4.2.

$$\frac{p(t+1) - p(t)}{p(t)} = r - (1+r)^{t+1}\frac{\mu_b(t)}{p(t)}. \tag{4.6}$$

In a setup in which the total number of allowances is available at all points in time, the price would increase with the interest r in line with Hotelling (1931). In the setup of the EU ETS borrowing is not allowed. $\mu_b(t)$ can be interpreted as the shadow costs of the borrowing constraint. If firms would optimally abate less than allowances are available, then the constraint on borrowing is binding. This occurs when the private bank is empty, i.e. $b_t = 0$. In this case the price increases at a lower rate than r.

4.3.3. Market Stability Reserve and Cancellation Mechanism

The EU introduced the Market Stability Reserve and the Cancellation Mechanism with the aim to stabilize allowances supply in the EU ETS. The combined mechanism of MSR and CM adjusts the allowances supply as reaction to the total number of allowances in circulation $TNAC(t) = Nb(t)$.

According to the EU COM's reform proposal, if at any point of time t the TNAC is higher than a threshold ℓ_{zone}, allowances enter the MSR in the following year instead of being auctioned. Under the 2018 regulation, MSR intake is a share $\gamma(t)$ of the TNAC. The reform proposal suggests introducing a buffer zone such that if the TNAC is in a range between ℓ_{zone} and ℓ_{up}, the MSR intake only amounts to the difference between the TNAC and ℓ_{zone}. Above ℓ_{up}, the intake increases to a share $\gamma(t)$ of the TNAC for both the 2018 regulation and the reform proposal. The auction volume $I_{auct}(t)$ decreases by the same amount of allowances. Under both regulations, if $TNAC(t)$ is below a lower threshold ℓ_{low}, R allowances from the MSR are added to the auction volume of the following year (European Parliament and the Council of the European Union (2015) and European Commission (2021d)).[38]

The CM determines that allowances are cancelled from the MSR, i.e. are rendered invalid, if the MSR exceeds a limit of ℓ_{cancel}. Under the regulation in place, ℓ_{cancel} is set at the previous year's auction volume. The proposed reform fixes the threshold ℓ_{cancel} at 400 million allowances (European Parliament and the Council of the European Union (2018) and European Commission (2021d)).

In the model, the endogenous supply of allowances is expressed by

$$I(t) = I(t-1) - \alpha(t)I_0 - Intake(t) + Reinjection(t). \tag{4.7}$$

[38] The threshold for MSR intake ℓ_{zone} is 833 million and the upper threshold ℓ_{up} under the reform proposal is 1096 million allowances. The intake share $\gamma(t)$ is 24% until 2023 and 12% afterwards under the regulation in place. The EU COM proposes maintaining $\gamma(t)$ at a level of 24% until 2030. The reinjection is triggered at a lower threshold ℓ_{low} of 400 million allowances and comes at yearly tranches R of 100 million allowances (European Parliament and the Council of the European Union (2015) and European Commission (2021d)).

The MSR volume is then given by

$$MSR(t) = MSR(t-1) + Intake(t) - Reinjection(t) - Cancel(t), \tag{4.8}$$

with

$$Intake(t) = \begin{cases} \gamma(t) * TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ 0 & \text{else,} \end{cases} \tag{4.9}$$

for the 2018 regulation and

$$Intake(t) = \begin{cases} \gamma(t) * TNAC(t-1) & \text{if } TNAC(t-1) \geq \ell_{up}, \\ TNAC(t-1) - \ell_{zone} & \text{if } \ell_{up} > TNAC(t-1) \geq \ell_{zone}, \\ 0 & \text{else,} \end{cases} \tag{4.10}$$

for the reform proposal as well as rules for reinjection and CM of

$$Reinjection(t) = \begin{cases} R & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) \geq R, \\ MSR(t) & \text{if } TNAC(t-1) < \ell_{low} \wedge MSR(t) < R, \\ 0 & \text{else,} \end{cases} \tag{4.11}$$

$$Cancel(t) = \begin{cases} MSR(t) - \ell_{cancel} & \text{if } MSR(t) \geq \ell_{cancel}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.12}$$

4.3.4. Model implementation and parametrization

The model is implemented and solved by GAMS and CPLEX as a mixed-integer linear program. The non-linear regulatory decision rules in both the regulation in place and the reform proposal are linearized using binary variables and the big-M method.

Following Bocklet et al. (2019), the numerical model uses an interest rate of $r = 8\%$, baseline emissions of $u = 2000$ million $CO_2eq.$ and a cost parameter $c = 0.75$ that leads to costs of the backstop technology of 150 Euro per ton.

The updated model starts in 2021 for both regulations and adjusts the cap to account for the withdrawal of installations from the United Kingdom. The 2021 cap therefore decreases to 1,572 million allowances (European Commission, 2021e).

The MSR started in 2019 with an initial endowment of 900 million allowances from backloading between 2014 and 2016 (European Parliament and the Council of the European Union, 2015) and 600 million not allocated allowances from phase III of the EU ETS (European Commission, 2015). The starting value for the MSR volume in 2021 is 1925 million allowances (European Commission, 2021a). In 2021, the MSR intake is 333 million allowances.[39]

4.4. Results

This section decomposes the overall effects of the reform into the individual effects of the different amendments. For this purpose, the research sets up four different scenarios, depicted in table 4.1. The *2018 regulation* scenario represents the current status of the EU ETS with a LRF of 2.2% and the existing implementation of the MSR and CM as outlined in section 4.2. The *Increased LRF* scenario updates the climate target of the *2018 regulation* scenario to a LRF of 4.2% until 2030 and of 2.0% afterwards. The *New MSR* scenario extends the *Increased LRF* scenario by including the new MSR intake rules in accordance with the 'Fit-for-55' proposal described in section 4.2. The *Fit for 55* scenario includes all three reform elements and thus entails a CM with a fixed cancellation threshold of an MSR volume above 400 million allowances.

	LRF	**MSR**	**CM**
2018 regulation	2.2 until 2057	ℓ_{up} = 833 million EUA $\gamma = 0.12$ after 2023	MSR > TNAC(t-1)
Increased LRF	4.2 until 2030 2.0 until 2050	"	"
New MSR	"	ℓ_{zone} = 833 million EUA ℓ_{up} = 1,096 million EUA $\gamma = 0.24$ after 2023	"
Fit for 55	"	"	MSR > 400 million EUA

Table 4.1.: Scenario overview

[39] In reality, MSR intake is determined for a period from September of one year to August of the next year. However, MSR volume for the cancellation mechanism is the end value of each year. To adjust this MSR intake to a yearly basis, the model uses for 2021 the January to August 2021 value from 2020's Communication C(2020) 2835 adjusted by Notice 2020/C 428 I/01 plus an estimate for MSR intake from 2021's Communication C(2021)3266. The estimate uses the 2020 share of the September to December intake from the 2020's Communication total intake.

4.4.1. Increased linear reduction factor

To assess the impact of the increased LRF on its own, the *Increased LRF* scenario is compared to the *2018 regulation* scenario. The increased LRF applied ex-ante, i.e. without MSR movements and cancellations, leads to a 62% emissions reduction in 2030 and climate neutrality in 2050. In total, it causes a reduction of overall allowance supply by 10,100 million allowances, or 34.2%, compared to the counterfactual *2018 regulation* scenario in which the 2.2% LRF is extrapolated until allowance supply becomes zero. Figure 4.1 contrasts the ex-ante allowance supply of the two scenarios. It becomes apparent that while the existing regulation achieves climate neutrality in the EU ETS sectors in 2058, climate neutrality in 2050 requires a significant reduction of the allowance cap. With a LRF of 4.2% until 2030, the climate neutrality target for 2050 can be achieved with a lower LRF of 2.0% after 2030.

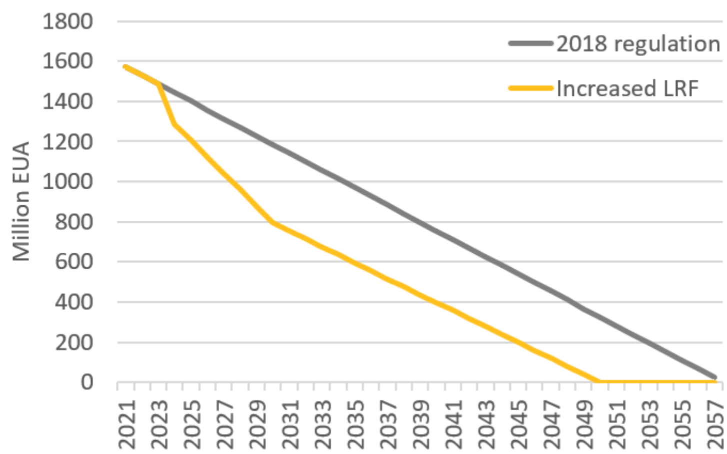
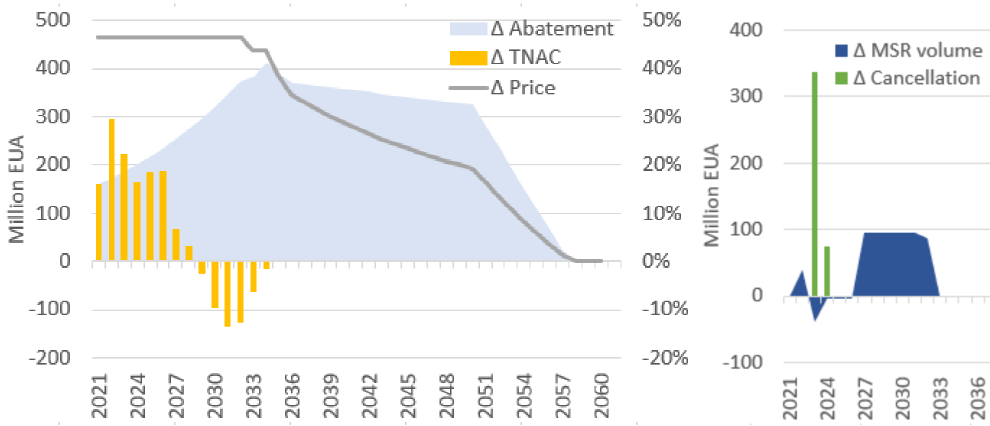


Figure 4.1.: Ex-ante allowance supply under the 2018 regulation and the Fit for 55-proposal

Figure 4.2 highlights the differences in the model results of the two scenarios. The tightening of allowance supply leads to an increase of the allowance price over the model horizon. The 2021 price level is 46.4% higher with the new target. Accordingly, abatement is shifted forward and increases proportionally to the price increase. The emission level reduces to zero already in 2050 under the increased LRF; i.e., firms do not bank allowances for the time the allowance supply is zero.

The higher price and, hence, abatement level lead to a higher TNAC from 2021 to 2028. This, in turn, triggers more and longer MSR intake. While under *2018 regulation* intake takes only place in 2021 and 2022, it is prolonged until 2024 in the *Increased LRF* scenario. This leads to a higher cancellation volume with the new target. Notably, the longer intake period leads to lower auction levels in 2023, thus triggering additional cancellation in 2024. The aggregate cancellation volume increases from 1,945 to 2,355 million EUA, i.e. by 21%. As the rules for MSR intake and cancellation do not change between the two scenarios, the MSR volumes after the cancellation in 2023 do not vary significantly. The higher TNAC in the *Increased LRF* scenario leads to a later start of reinjection of MSR allowances into the market in 2028 compared to 2027 in the *2018 regulation* scenario. In the long run, the lower allowance supply leads to a quicker depletion of the TNAC such that, after 2028, its level is lower under *Increased LRF* than under *2018 regulation*.



(i) Allowance market (ii) MSR movements

Figure 4.2.: Results of *Increased LRF* minus *2018 regulation*

The increased LRF ex-post misses its aim of a 61% emission reduction compared to 2005 levels. While the ex-ante cap overachieves the targets with a 62% reduction, the resulting emission level in 2030 only achieves a 58% emission reduction. Not only use firms allowances from the TNAC in 2030 but the climate target year lies moreover in the period of MSR reinjection. In other words, the MSR impedes the achievement of the climate target for 2030. This confirms the results from Osorio et al. (2021) that a LRF of 5.1% would be needed to achieve an emission reduction of 63% under the EU ETS.

4.4.2. Revised MSR regulation

As explained in detail in section 4.2, the reform proposal suggests to adjust the current MSR regulation in two ways: First, a buffer zone shall be introduced to reduce price volatility by enabling a smooth increase of the intake level instead of the hard threshold of the 2018 regulation. Under the 2018 regulation, MSR intake increases for an additional unit of TNAC above the threshold from zero to a significant number. Under the 'Fit for 55' proposal, intake is in the same case only one allowance - the difference between the threshold and the TNAC. Second, the reform proposes to increase the MSR intake rate from 12 to 24% with the aim to reduce the number of allowances in the market.

The model results show that the proposed *New MSR* regulation does not significantly change the MSR intake compared to the 2018 regulation ceteris paribus. Figure 4.3 presents the difference in MSR intake between the *Increased LRF* and the *New MSR* scenarios. The intake values under the *New MSR* decrease by 0.2% for 2022 and by 0.5% for 2023 as the reform proposal only takes effect in 2024. Even if the reform proposal took effect in 2021, MSR intake would only change negligibly as the TNAC in 2021 is above and in 2022 only slightly under the upper threshold of TNAC. Above this threshold, the two MSR designs do not differ at a given intake rate. Despite the same intake rule in both scenarios for 2022 and 2023, there is a slight difference in the intake values that is caused by the firms' expectation of the change in regulation after 2023.

In 2024, the model estimates a decrease from 108 to 57 million allowances intake in the MSR induced by the proposed change in the regulation. At a TNAC of 897 or 890 million allowances, respectively, in 2023, intake at a rate of 12% in line with the regulation in place is significantly higher than with an intake under *New MSR* (of the difference of the previous year's TNAC and 833 million allowances). We can, however, not conclude that the proposed MSR will in all cases lead to less intake. For a TNAC above 947 million allowances, the proposed regulation leads to more intake than the current regulation with a 12% intake rate.[40] The increase of the intake rate from 12 to 24% from 2024 onward has in the model no effect as intake in any case ceases after 2024 due to the low level of TNAC associated with the more ambitious climate target.

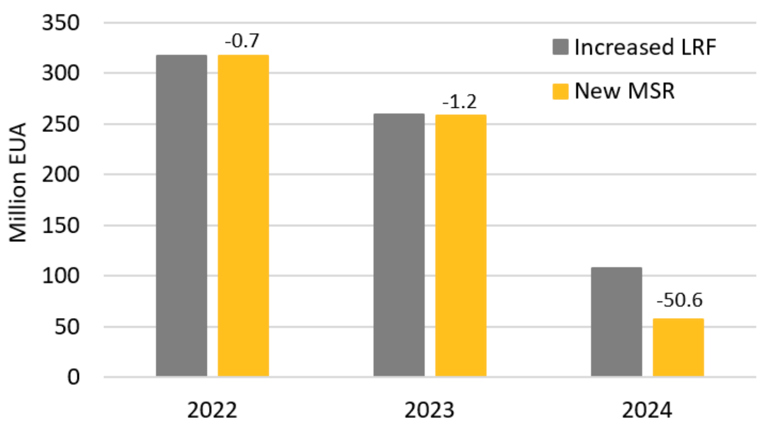
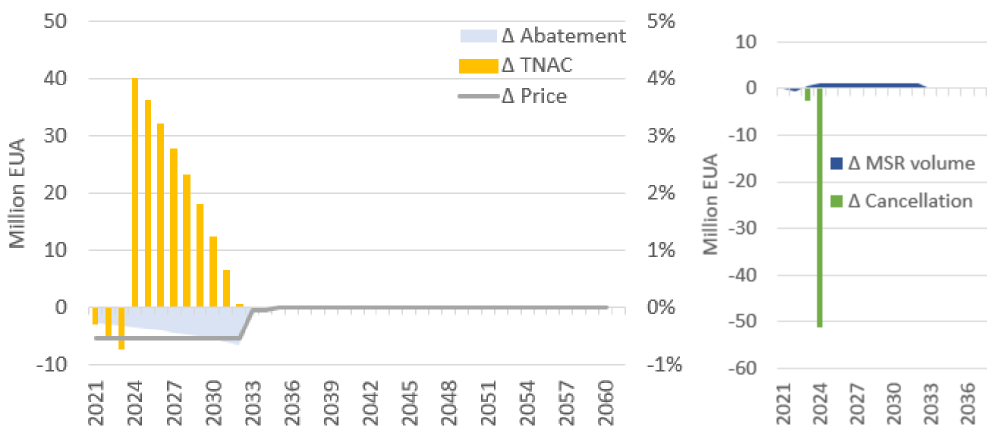


Figure 4.3.: MSR intake under *Increased LRF* and *New MSR*

Figure 4.3 presents the differences between the *Increased LRF* and the *New MSR* scenarios in detail. As the cancellation mechanism does not vary between the two scenarios, the lower MSR intake presented in Figure 4.3 translates directly into a cancellation volume that is by 53.7 million allowances lower in *New MSR* than in the *Increased LRF* scenario. In perfect foresight of the higher allowance

[40] At an intake rate of 24% under the regulation in place, in contrast, the proposed transition zones leads in all cases to a lower intake.

supply in *New MSR*, the price starts at a slightly lower level. The lower price induces lower abatement in *New MSR* compared to *Increased LRF* in all years. Less abatement leads to a lower TNAC from 2021 to 2023. In 2024, the changed MSR intake rules with less intake in *New MSR* boost the TNAC level compared to the *Increased LRF* but the higher TNAC levels deplete in the following years because of the lower abatement. Price levels are identical again once the TNAC and MSR become zero in 2034 in both scenarios as the abatement and price levels are determined by the allowance supply. While the direction of change induced by the proposed adjustment of the MSR is ambiguous, it is worth noting that the difference in the results of the two scenarios are lower than 1% and hence negligible. The adjusted MSR intake rules have no significant impact on the EU ETS market outcome.



(i) Allowance market (ii) MSR movements

Figure 4.4.: Results of *New MSR* minus *Increased LRF*

The EU COM states the aim of the buffer zone as reducing price volatility. Price volatility describes historical price movements over a longer period that cannot be assessed in a simulation model. We follow the interpretation of Perino and Willner (2016) that the EU COM's concept of market stability rather refers to the absolute price change in response to shocks, i.e., price variability. We can further say that an unexpected change in allowance supply constitutes a system-inherent shock. Figure 4.5 provides a first idea of the impact of the buffer zone on allowances supply. It shows that, while its introduction in *New MSR* smooths allowance supply and hence should reduce price variability, the effect is only visible in 2024.

To further assess the MSR reform's impact on price variability, we can extend the findings of Perino and Willner (2016) to the proposed regulation. The authors find that the MSR in its current regulation increases price variability in case of a shock. The MSR has accordingly a destabilizing effect on the allowance market. Independent of our model results, we can conclude from the findings of Perino and Willner (2016) that a reform reducing the impact of the MSR must increase

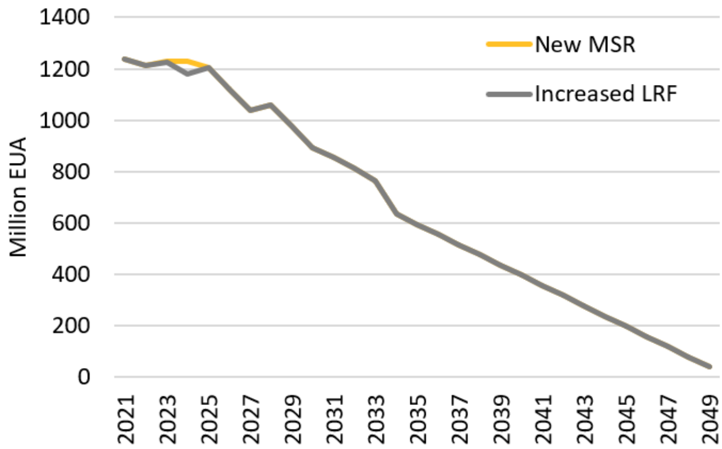


Figure 4.5.: Ex-post allowance supply under *Increased LRF* and *New MSR*

the market's resilience, while the destabilizing effect is more pronounced if the impact of the MSR is stronger. The impact of the reform proposal is hence ambiguous as the MSR intake is lower for a TNAC between 833 and 947 million allowances and higher above this level.

Perino and Willner (2016) focus on demand-induced shocks, e.g., economic crises or overlapping policies. The MSR reform proposal, however, is not directed at addressing this type of shocks. Its intention is rather to reduce the uncertainty regarding the level of MSR intake and this objective is achieved. We can therefore conclude that while the reform proposal may not increase the general resilience to shocks and even deteriorate it, it reduces price variability induced by uncertainty regarding the MSR intake and hence increases market stability.

We find this ambiguous impact also for the second aim of the MSR adjustment, the reduction of allowance supply. Introducing a buffer zone increases allowance supply. This effect may be offset and even overcompensated by the increase of the intake rate from 12% to 24%.

4.4.3. Revised Cancellation Mechanism

Regarding the revision of the cancellation mechanism, economic intuition suggests that a cancellation threshold of 400 million allowances compared to the previous year's auction volume from the current regulation would significantly increase the cancellation volume. However, the increase induced by the revised cancellation mechanism only amounts to 3.2% of the total cancellation volume. Figure 4.6 shows that while in the *Fit for 55* scenario cancellation volumes increase in 2023 and 2024 compared to the *New MSR* scenario, the cancellation in 2025 decreases to zero in both scenarios. With a fixed cancellation threshold, the first cancellation limits the MSR volume to 400 million allowances and, in consequence, further cancellation only takes place in years with MSR intake. As the last year of MSR intake in *Fit for 55* is 2024, there is no cancellation after this year. A sensitivity analysis in C.1 shows that even an extreme threshold of zero would not have a significantly higher cancellation volume, as the 'Fit for 55' proposal can only enter into force by 2024 and the cancellation volume depends more on the MSR intake than on the cancellation threshold.

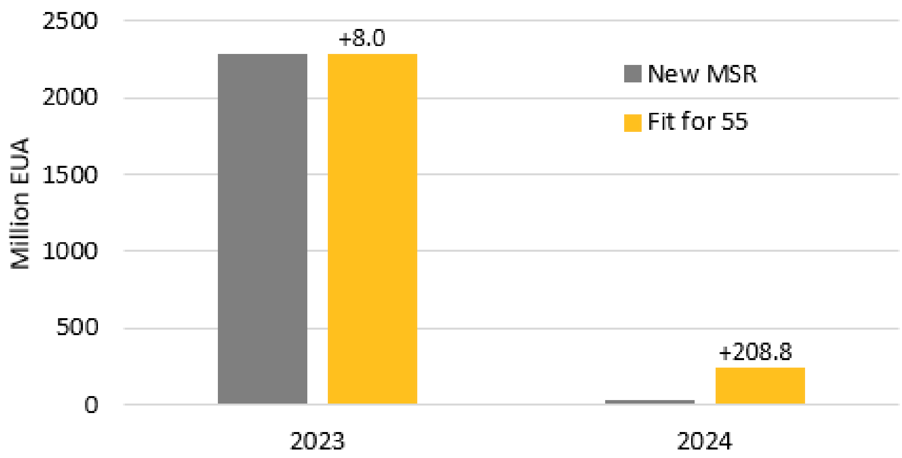
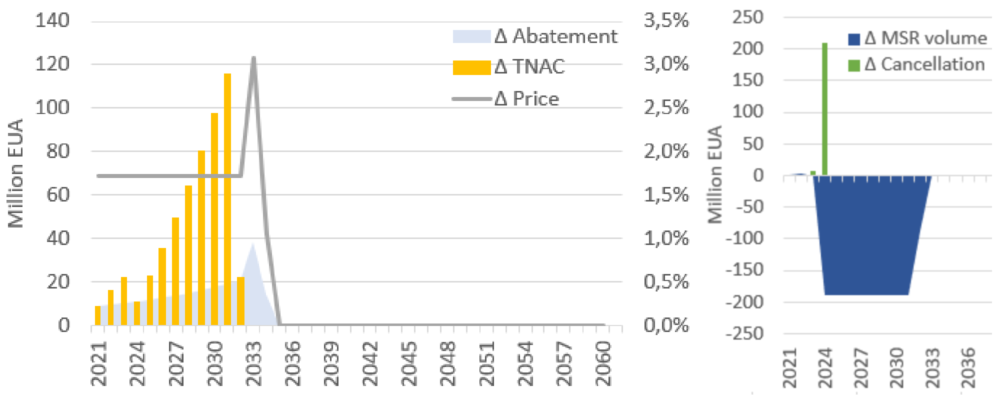


Figure 4.6.: Cancellation volume under 2018 regulation and Fit for 55-proposal

Figure 4.7 presents the differences between the *New MSR* and the *Fit for 55* scenarios in detail. The expectation of a higher cancellation volume leads to higher prices and consequently more abatement in the *Fit for 55* scenario. The lower cancellation in *New MSR* leads to a higher remaining MSR volume after the cancellation and allows for a two years longer reinjection period from 2028 to 2033, instead of 2031 in *Fit for 55*.[41]



(i) Allowance market (ii) MSR movements

Figure 4.7.: Results of *Fit for 55* minus *New MSR*

[41]This explains the spike in the price difference as the reinjection allows for a longer maintenance of a Hotelling price path in *New MSR*.

The model results show that the proposed fixed cancellation threshold of 400 million allowances leads to a higher cancellation volume compared to the current threshold which is defined by the previous year's auction level. This is not necessarily the case under other circumstances. In the model setup, there is no additional MSR intake after 2024 and, hence, cancellation only takes place in 2023 and 2024, both under the 2018 regulation and the proposed reform. While the cancellation volume in the first years is in all cases higher under the proposed fixed cancellation threshold of 400 million allowances, there could be additional cancellation under the 2018 regulation but not under the proposed reform later in the case of an MSR volume below 400 and a previous year's auction level that is even lower.

4.4.4. Scenario comparison

To understand the impact of the individual reform elements, this subsection compares the four scenarios regarding the model results for emission reduction, EUA prices and cancellation volume. Figure 4.8 shows that all scenarios significantly fall short of the 61% climate target of 2030. While this is not surprising for the *2018 regulation* scenario that aims at a reduction of 43%, the increased LRF can only partially close the gap. The adjusted MSR and CM have only a minor additional impact on the 2030 abatement level.

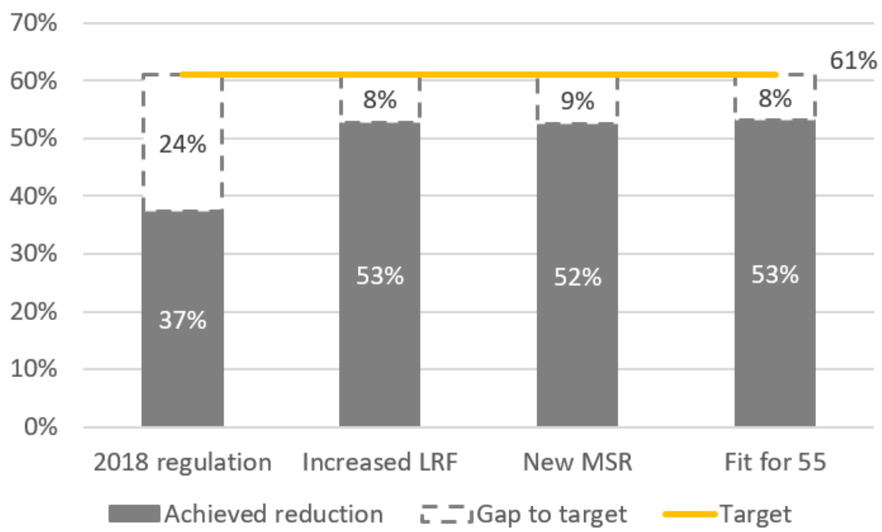


Figure 4.8.: Achieved versus target reduction for 2030 in the four scenarios

Figure 4.9 indicates the impact of the reform elements on the 2021 allowance price level. While the reform as a whole increases price levels by 48%, 46 percentage points of these can be attributed to the increased LRF. In *New MSR*, the proposed MSR rules decrease the price level by one percentage point as the MSR intake is lower than in *Increased LRF*. The increased cancellation volume in the *Fit for 55* scenario increases the 2021 price level by only 3 percentage points.

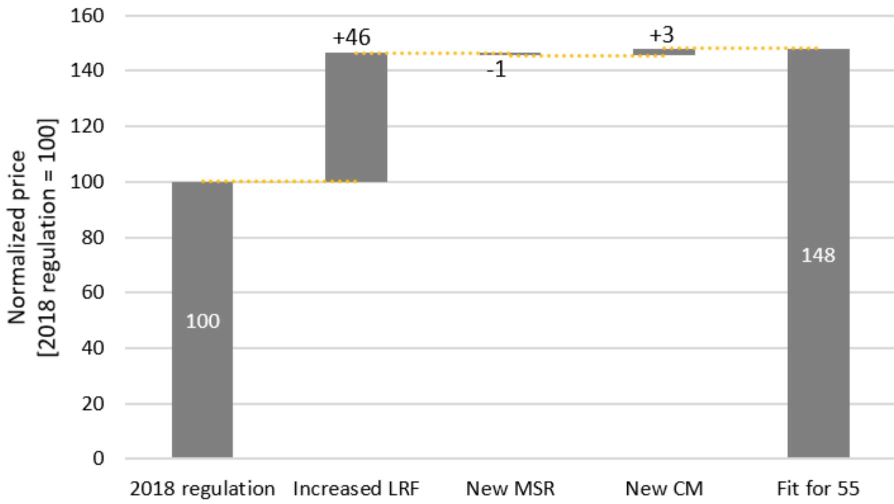


Figure 4.9.: Decomposition of changes in 2021 price level into the individual reform elements

While the impact of the MSR and CM adjustments on abatement and price levels are minor compared to the impact of the increased LRF, all three reform elements have significant effects on the aggregate cancellation volumes. Figure 4.10 shows how the total increase in cancellation volume of 563 million allowances can be attributed to the different elements of the reform proposal. The main share of the increase (410 million allowances) stems from the increased LRF. The proposal for an adjusted MSR regulation, in contrast, reduces the overall cancellation by 54 million and the new CM rules lead to an increase of 217 million allowances. Analogously, C.2 presents a decomposition of the impact of the reform proposal into the three reform elements regarding total emissions and the 2021 abatement level.

4.5. Discussion

4.5.1. Critical model assumptions

The model results show a limited impact of the proposed change in MSR and CM rules. However, this may to a large extent depend on the model assumptions of constant baseline emission level and a linear MAC curve. Moreover, the research assumes rational firms with perfect foresight, neglecting the potential influence of bounded rationality aspects, like hedging behavior or myopia. The following subsection discusses how model results would change if these assumptions were relaxed and under which real-world circumstances this might be the case.

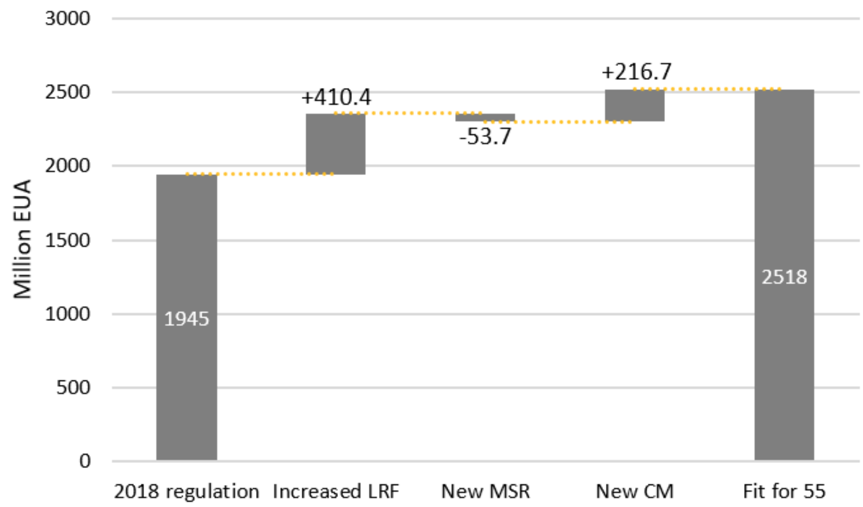


Figure 4.10.: Decomposition of changes in cancellation volume into the individual reform elements

Baseline emissions may change over time in response to the development of the economy or to overlapping policies. The impact of these changes in baseline emissions on the outcome of the EU ETS and the effect of the reform proposal depends on two factors: the duration of the change in baseline emissions (temporary or permanent) and the market's anticipation of these changes. For instance, in the case of a sudden economic crisis or a similar shock to emissions baseline emissions may drop abruptly but also recover quickly.[42] In consequence, the TNAC might increase to levels above 833 million allowances and there might be an additional phase of MSR intake. In this case, all allowances transferred to the MSR are automatically cancelled under the proposed CM. Under the existing regulation, the impact of a short-term crisis is less clear as the cancellation depends on the previous year's auction level, i.e., the timing of the demand shock. Thus, the proposed adjustment increases predictability of the cancellation mechanism also in this case.

Overlapping policies or long-term changes in the structure of the economy may affect the level of baseline emissions more permanently than economic crises. For instance, higher levels of RES or lower electricity demand reduce baseline emissions and vice versa. The outlined effects would be more pronounced but go in the same direction as for a temporary baseline emissions shock. However, particularly with overlapping policies, it is likely that market agents anticipate these changes of baseline emissions. In this case, the price and abatement paths would adjust already before the change occurs. Anticipated overlapping policies that reduce baseline emissions can therefore decrease price and abatement levels along the entire EU ETS horizon and even lower the cancellation volume

[42]More generally speaking, economic crises can take different shapes of recovery. See Bocklet (2020) for an analysis of different types in the context of the EU ETS.

compared to a benchmark without the overlapping policies. Rosendahl (2019) and Schmidt (2020) provide analyses of this so-called New Green Paradox. The proposed adjustment of the MSR and CM rules cannot overcome this problem.

The model results further depend critically on the assumption of the functional form of the MAC curve. The slope of the MAC curve determines how abatement is distributed over time. The model uses a smooth synthetic MAC curve with a linear slope. This assumption may not hold in reality, as Hintermayer et al. (2020) indicate. We can qualitatively assess the impact deviations from this assumption. An overall steeper or flatter linear MAC curve is equivalent to a change in backstop costs and has no impact on the distribution of abatement over time, as Bocklet et al. (2019) show. If, however, only the low-cost segment of the MAC curve becomes flatter, for instance induced by a smaller gas-coal-spread for electricity generation, while the costs of abatement options in the high-cost segment of the MAC curve are unchanged, firms would shift abatement efforts forward. This, in turn, would increase TNAC, MSR intake and cancellation volumes.

Considering elements of bounded rationality like hedging of allowances and myopic behavior would influence the model results. Hedging means that firms hold a certain share of allowances in their private bank to protect themselves against EUA price increases. This behavior increases the TNAC levels. As Bocklet and Hintermayer (2020) show, this leads to a higher intake into the MSR and a higher cancellation volume. Hedging behavior thus increases the impact of the increased LRF. Myopic behavior, in turn, leads to more emissions in the short run as firms do not take into account future scarcity of allowances. This potentially dampens the impact of an increased LRF with fewer MSR intake and cancellation volume. Both elements of bounded rationality should not change the findings regarding the effectiveness of the reform elements. Hedging or myopia do not affect the achievement of climate targets neither the level of (short-term) predictability of the CM. It could have a small effect on the level of MSR intake or the change in price variability induced my the proposed MSR reform but the change could go in both directions.

4.5.2. Potential shortcomings of the proposed reform elements

The model results in section 4.4 indicate that the individual reform elements may not fully achieve but work towards reaching their goals and are thus largely effective. Altogether, the proposed EU ETS reform should therefore strengthen the EU ETS as key instrument of EU climate policy. This subsection discusses potential shortcomings of the reform regarding the efficiency of its intended goals.

For the (over)achievement of a 61% climate target by 2030, the LRF increases from 2.2% to 4.2%. To achieve climate neutrality by 2050, the LRF would again decrease from 4.2% to 2.0%. Whether it is optimal that the allowance supply starts to decrease at a high rate and then to slow down ambition depends on various factors and cannot be determined within the analysis at hand. As illustrated in Bocklet et al. (2019), the optimal timeline for allowance supply would be to issue all allowances at the beginning of an ETS. This approach allows firms to allocate the emissions budget freely over time. Setting up an annual cap, in turn, leads to a significant loss of cost-effectiveness as it restricts the allocation of emissions over time. However, issuing all allowances at the beginning of an ETS is a theoretical benchmark that can only be effective if a government can fully commit to an ETS and firms believe that there will not be further interventions. In reality, a cap with a predetermined cap reduction is likely to be the more effective policy approach.

The MSR reform proposal smoothens the intake rules and effectively eliminates threshold effects, thereby decreasing price variability. However, there is an inherent trade-off between the two goals of the MSR, low price volatility and regulation of allowance supply. Any deviation from the predetermined allowance cap that is not fully predictable for market participants may constitute a supply shock that increases price variability. Osorio et al. (2021) confirm this by computing MSR and cancellation volumes for a range of parameter constellations. They find that the results are highly uncertain and that thus these instruments induce uncertainty regarding the allowance price. The proposed adjustment can mitigate but not overcome this trade-off. In the same vein, Salant (2016) discusses that any sort of additional regulatory intervention in an ETS has a destabilizing effect leading to inefficiently high total abatement costs. In this sense, there is a trade-off between the small overall positive impact of the proposed adjustments to the MSR and CM mechanisms and the negative impact of potentially increasing regulatory risk in the market by again changing the regulation in place.

In a similar way, the proposed reform falls shorts of addressing the inconsistency of the current hybrid approach of the EU ETS with an orientation towards both an emissions budget over the system's overall time horizon and annual climate targets. The EU ETS is budget-oriented as it provides the option to bank allowances but it also aims at fixed annual climate targets. Banking provisions increase the economic efficiency of emissions trading system. However, they explicitly allow for emissions to be higher than a fixed annual cap.[43] Likewise, the MSR and CM focus on allowance supply in specific years and aim to limit banking of allowances. Osorio et al. (2021) propose that the adjustment of the LRF should take into account MSR and CM movements in order to achieve the 2030 emission target. However, the most accurate models can never predict the exact emission level of a specific year and hence even meticulous adjustments of the LRF, MSR and CM rules cannot guarantee that the 2030 climate target is achieved.

[43]Note that the contribution of the EU ETS to EU climate targets is further uncertain as the EU ETS covers not only the EU but also Norway, Liechtenstein and Iceland.

4.6. Conclusion

The research at hand applied a discrete-time optimization model of the EU ETS to assess the impact of the EU ETS reform proposed in the 'Fit for 55' package of the European Commission as a whole and to decompose the effects of the three main reform elements. The model results indicate a significant impact of the reform with 48% higher prices in 2021 under the proposed reform than under the 2018 regulation. While this is clearly not the only factor that has influenced 2021 price levels, the model results suggest that market participants expect the reform to enter into force and significantly influence EU ETS market outcomes. The results further show that the increased linear reduction factor has by far the largest impact on the EU ETS market outcome, driving 46 percentage points of the 48% price increase. In comparison, the adjustment of the MSR intake rules and the CM has only a smaller impact of together two percentage points.

The model results indicate that the proposed adjustment of the EU ETS mechanisms strengthen the EU ETS as key instrument of EU climate policy. The reform raises the climate ambition of the EU ETS, increases the predictability of the cancellation mechanism and eliminates threshold effects in the MSR intake under the regulation in place that may destabilize the market outcome. Nevertheless, the achieved improvements may be of limited impact. The adjusted MSR intake leads to a significant change only in 2024 as there is no further MSR intake afterwards under the old and new MSR rules. Similarly, the fixed threshold for cancellation leads only to a higher cancellation volume in its introduction year 2024. Further cancellation would only take place if there was additional MSR intake. This is not the case under the model configurations. The increased LRF reinforces the low impact of the MSR and CM it decreases TNAC levels. The increased climate targets may render the other proposed reform elements unnecessary.

The reform may not fully achieve its goals. The model results show that the increased linear reduction factor does not ensure the achievement of the new climate target for 2030. The emissions level in the target year may be higher as firms may use their banked allowances and allowances from the MSR may be reinjected into the market. While this may not be a serious flaw of the EU ETS from an economic point of view, it is a drawback for a reform labeled 'Fit for 55'. Furthermore, the impact of the proposed adjustment of the MSR intake on reducing allowance surplus and decreasing price volatility is ambiguous. The introduction of the buffer zone smooths allowance supply as it prevents threshold effects caused by the current regulation. However, it may also reduce MSR intake and cancellation. Decreasing price volatility through the buffer zone may hence be in conflict with the other MSR goal of reducing the number of allowances in circulation.

The underlying reason of the inability of the reform to achieve its goals is the hybrid nature of the EU ETS combining elements that orient towards an overall emissions budget and others that focus on the achievement of annual emissions targets. While the intertemporal nature of emissions trading system inhibit precisely targeting annual emissions reductions, the uncertainty induced by the MSR and Cancellation Mechanism further complicates this endeavour. EU ETS reforms need to constantly balance both approaches that are partially in conflict. While economic theory favors a budget approach, political commitment problems as well as providing optimal incentives for innovation and learning by doing favor a system with annual targets. Further research is needed to understand the optimal balance between the two approaches. In particular, there is still a lack of understanding how allowance supply in emissions trading systems should be regulated in order to ensure optimal abatement paths beyond the Hotelling rule of resource extraction.

5. Complementing carbon prices with Carbon Contracts for Difference in the presence of risk - When is it beneficial and when not?

5.1. Introduction

The decarbonization of the industrial sector requires substantial investments throughout the next decade (IEA, 2021). These investments are typically irreversible decisions that firms have to take in the presence of risk. The risk of an investment's profitability in a decarbonizing world mainly stems from two sources:

First, the profitability of investments in low-carbon or emission-free technologies depends on carbon prices. These technologies are only competitive with conventional technologies if the carbon price throughout the asset's economic life reaches a certain level. However, carbon prices may feature risk. One reason is that the expected carbon damage may change as new scientific evidence on climate change emerges.[44] Another reason is the potentially changing public valuation of carbon damage, shown by court rulings on climate policy in 2021 in Germany (Bundesverfassungsgericht, 2021, Economist, 2021). Both circumstances create a *damage risk*. Firms facing irreversible investments are exposed to such a damage risk as the regulator may adjust the carbon price according to these changes. In fact, Chiappinelli et al. (2021) report that four out of five firms state that the lack of effective and predictable carbon pricing mechanisms is a major barrier to low-carbon investments. López Rodríguez et al. (2017) or Dorsey (2019) provide further empirical analysis that firms reduce their investments due to environmental regulation-related risks.

Second, there is a *variable cost risk*. Variable costs of low-carbon technologies are not fully known, as adopting innovative production processes may involve novel input factors. The markets for some of these input factors are highly immature, the most prominent example being green hydrogen. The production costs of hydrogen might vary depending, e.g., on the costs of electricity or transport (Brändle et al., 2021). Additionally, there is an active and ongoing market ramp-up involving multiple stakeholders to facilitate technological learning (Schlund

[44] For instance, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change concludes that the climate system is warming faster than previously estimated (IPCC, 2021). Furthermore, OECD (2021) highlight the risks to predict the environmental damage due to the complex climate dynamics.

et al., 2021). Hence, the market for hydrogen is still at the beginning of organizing itself (International Energy Agency, 2019).

Firms' possibilities to hedge against these risks are limited or prohibitively costly.[45] For instance, in the European Emission Trading System (EU ETS), the availability of futures contracts with a maturity longer than three years is low (Newbery et al., 2019).[46] Similarly, there are limited hedging possibilities against variable cost risk from novel input factors traded on immature markets (OEIS, 2021). The described risks and the missing hedging possibilities deter firms from investing, which, in turn, poses a challenge to decarbonization.

To nevertheless facilitate and incentivize large-scale investments in the presence of such risks, the European Commission's Hydrogen Strategy and the reform proposal for a *Fit for 55* package, suggest Carbon Contracts for Differences (CCfDs) as a support scheme for firms in the industry sector (European Commission, 2021e). CCfDs are contracts between the government and a firm that pay out the difference between a guaranteed price, the so-called *strike price*, and the actual carbon price, per tonne of emission reduction delivered by the firm through a low-carbon project. The contracts can be interpreted as a short position in a forward on emission permits. Therefore, CCfDs are effectively a hedging instrument to reduce the firms' risk when making investment decisions. Besides their hedging properties, CCfDs may contain a subsidy for decarbonization investments.[47] Such subsidies may be justified by, e.g., positive externalities. In this paper, we do not consider such externalities, and, hence, CCfDs mainly serve as hedging instrument in our setup. So far, there is only a limited understanding of how regulators should design such instruments and under which circumstances the introduction of CCfDs is welfare-enhancing.

In this paper, we analyze how different sources of risk affect the efficiency of CCfDs and when these contracts are preferable to other policies, like committing to a carbon price early on or a flexible carbon pricing regime. We develop an analytical model in which a regulator sequentially interacts with a continuum of risk-averse firms. These firms can either supply the market with a conventional technology, which causes carbon emissions subject to carbon pricing, or invest in an emission-free technology. The valuation of environmental damage from carbon emissions and the variable costs of the emission-free technology may be subject to risk. The firms are heterogeneous regarding their investment costs when adopting the emission-free technology. Firms invest if they increase their expected utility by adopting the emission-free technology. The regulator maximizes social welfare by choosing one out of three carbon pricing regimes: 1) setting a carbon price

[45] If markets were complete, a perfect hedge of all relevant factors determining an investment's profitability would always be possible (Arrow and Debreu, 1954). Thereby, the profitability of abatement investments would not be volatile, and investments would be made as long as they are profitable in expectation without the impact of risk.

[46] There are several reasons why forward markets for emission allowances are incomplete (e.g. Tietjen et al., 2020, for a survey).

[47] This is the case for the German and EU Hydrogen Strategy, as well as 'Fit for 55' package.

flexibly after the actual damage or costs are revealed (*Regulatory Flexibility*), 2) committing to a carbon price early (*Commitment*)[48], and 3) a hybrid policy regime containing a CCfD and flexible carbon pricing (*CCfD*). We compare these three carbon pricing regimes against the social optimum.

We find that under perfect foresight, i.e. in the absence of risk, all carbon pricing regimes result in the social optimum. In all regimes, the carbon price equals the marginal environmental damage of production. The marginal firm investing in the emission-free technology balances the marginal costs and the marginal benefit of abatement. This finding arises from two effects: First, because the regulator has perfect foresight, she can set the optimal carbon price level at any time. Second, firms do not face a risk in profits. Any risk would hamper firms' willingness to invest if they are risk averse.

We then assess the effect of risk and risk aversion on the performance of the three carbon pricing regimes. In a first setup, we assume that production of the emission-free technology is always socially optimal given the actual damage and variable costs. In these cases, offering a CCfD results in the social optimum irrespective of the source of risk. The regulator can incentivize socially optimal investments via the CCfD and adjust the carbon price according to the actual damage valuation. In contrast, both *Regulatory Flexibility* and *Commitment* fall short of reaching the social optimum. Which of the two regimes is welfare-superior depends on the source of risk. In case of damage risk, the welfare ranking is ambiguous and depends on the level of the firms' risk aversion (with high risk aversion favouring *Commitment*) and the elasticity of demand (with high elasticity favouring *Regulatory Flexibility*). In contrast, committing to a carbon price is welfare-superior to *Regulatory Flexibility* in settings with variable cost risk, as the regulator can incentivize additional investments under *Commitment.*

Lastly, we assess the effects of emission-free production that is potentially welfare reducing given the actual damage and variable costs. In this case, we find that offering a CCfD does not reach the social optimum. If the regulator offers a CCfD, the firms' production decision does not depend on the actual carbon price. Thereby, the regulator safeguards emission-free production even if it is socially not optimal ex-post. The same holds for *Commitment.* In contrast, under *Regulatory Flexibility*, the firm faces a carbon price equal to the social costs of carbon, such that it does not distort the production decision. Depending on the level of risk aversion and the probability of ex-post socially not optimal production, either *Regulatory Flexibility* or offering a CCfD is welfare superior.

Our paper contributes to two broad streams of literature in the context of irreversible investments in low-carbon technologies in the presence of risk.

The first literature stream focuses on policy options when firms face irreversible decisions. Baldursson and Von der Fehr (2004) analyze policy outcomes in a

[48]Literature suggests that regulators may have an incentive to deviate from announced carbon prices ex-post, implying regulators may not be able to credibly commit (e.g. Helm et al., 2003).

model in which firms choose between an irreversible long-term investment in abatement under risk and a short-term abatement option after the risk resolves. In the presence of risk aversion, the authors show that committing to a carbon tax ex-ante outperforms flexible carbon prices stemming from tradable permits because the latter increase the firms' risk exposure. Jakob and Brunner (2014) show that regulators can combine the advantages of flexibility and commitment by not committing to a specific climate policy level but a transparent adjustment strategy in response to climate damage shocks. In reality the regulator may need to address not only the optimal level of an irreversible investment decision but also the optimal consumption level. Höffler (2014) points out that regulators should address each target with a separate instrument. Therefore, a hybrid policy, i.e. the combination of two policies may be necessary. Offering a CCfD in addition to carbon prices constitutes a hybrid policy in the sense that the CCfD targets the firms' investment decisions while the complementary carbon price targets the optimal consumption level. Closely linked to our paper, Christiansen and Smith (2015) extend the analysis of Baldursson and Von der Fehr (2004) to hybrid policy instruments. The authors analyze a sequential setting in which firms initially have to decide on an investment in a low-carbon technology under risk and subsequently adjust output after the risk resolves. If a carbon tax commitment is the only instrument, the regulator sets the tax higher than the expected damage to incentivize more appropriate investments.[49] Supplementing the carbon tax with a state-contingent investment subsidy increases welfare as it allows for incentivizing investment without setting a carbon tax that is too high. In a similar vein, Datta and Somanathan (2016) analyze a carbon tax and a permit system and examine the role of research and development (R&D) subsidies. They conclude that using only one instrument cannot be welfare-optimal if the regulator aims to address two targets - the internalization of external effects from R&D and carbon damage. This is in line with our finding that a hybrid policy, in our case a CCfD, can improve welfare in a setting with an irreversible investment decision.

The second literature stream examines the role of hedging instruments for incentivizing investments in low-carbon technologies under risk. Within this literature stream, the introduction of hedging instruments are found to increase investments in the presence of risk aversion. Borch (1962), who analyzes reinsurance markets, demonstrates that players are willing to share risks according to their level of risk aversion by trading reinsurance covers which act as hedging instruments. This finding is supported by Willems and Morbee (2010), who examine investments in energy markets. The authors find that the availability of hedging opportunities increases investments of risk-averse firms and welfare. Habermacher and Lehmann (2020) analyze the interaction between a regulator

[49] This result resembles the insights from the real options literature where risk, combined with investment irreversibility, gives rise to an option value of waiting, e.g., Dixit et al. (1994). Chao and Wilson (1993) find an option value for emission allowances. Purchases of emission allowances provide flexibility to react to risk in a way that irreversible investments do not. The price of emission allowances may therefore exceed the marginal cost of abatement.

aiming to maximize welfare and firms facing an investment decision in low-carbon technologies. Similar to our paper, the authors assess carbon damage and variable costs risk. They find that the introduction of stage-contingent payments which partly hedge the risks of the regulator and the firm improve welfare compared to committing to carbon price or setting it flexibly. Those findings are in line with our result that a CCfD as an instrument for firms to hedge their risk leads to more investment and may increase welfare. Furthermore, hedging instruments may improve welfare even in the absence of risk aversion. An early example is Laffont and Tirole (1996), who show that the introduction of options solves the problems arising from strategic behaviour between the regulator and a firm.[50] If the regulator faces incomplete information, Unold and Requate (2001) show that offering options in addition to permits is welfare-enhancing. In contrast to this stream of literature, Quiggin et al. (1993) find that hedging instruments may also be welfare-deterring, as they may foster undesired behaviour. This result resembles our findings in the case of potentially ex-post welfare-reducing production in section 5.4.

CCfDs combine the effects of a hybrid policy and a hedging instrument. They recently gained attention from academic literature. Richstein (2017) focuses on the optimal combination of CCfDs and investment subsidies to lower policy costs and support investment decisions under risk and risk aversion. However, the study does not include the regulator's decision on the carbon price regime. To the best of our knowledge, Chiappinelli and Neuhoff (2020) provide the only study that explicitly analyzes CCfDs in the context of multiple carbon pricing regimes. The authors model firms which face an irreversible investment decision and behave strategically, which influences the regulator's decision on the carbon price. In this setup, higher investments in abatement technologies lead to lower carbon prices so that firms strategically under-invest to induce higher carbon prices. Offering CCfDs can alleviate such a hold-up problem. We build on the model developed in Chiappinelli and Neuhoff (2020) but change the focus of analysis. We analyze a setup with a large number of small firms in a competitive market. Chiappinelli and Neuhoff (2020) show how CCfDs can alleviate the hold-up problem that results from regulation and, hence, mitigate regulatory risk. In contrast, we focus on the impact of CCfD in an environment of risks that are outside the control of regulator and firms, i.e., damage and variable cost risk. We also present the first paper in this literature stream to point out that CCfDs can cause a lock-in in technologies that are ex post not socially optimal.

5.2. Carbon pricing regimes in the absence of risk

This section introduces the model setup to analyze the effects of CCfDs. In the model, we assess the interactions between a regulator and firms in the absence of

[50] This type of expropriation game constitutes a type of climate policy risk but mainly includes strategic behaviour.

risk. The regulator can apply three carbon pricing regimes to reduce emissions while firms face an irreversible investment decision to abate emissions during production.

5.2.1. Model framework in the absence of risk

We model the market for a homogeneous good G in which three types of agents participate - namely, consumers, firms, and a regulator. Consumers have an elastic demand $Q(p_G)$ for the good at a market price p_G. Demand decreases in the good's price, i.e., $Q'(p_G) < 0$.

A continuum of firms supplies the good in a competitive market. Each firm produces one unit. Initially, all firms produce the good with a conventional technology. Using the conventional technology to produce one unit of G induces constant marginal production costs ($c_0 \geq 0$) that are identical among all firms. The production process emits one unit of carbon emission. The emission causes constant marginal environmental damage d, which lowers the overall welfare, and is subject to a carbon price ($p \geq 0$). The resulting total marginal costs of the conventional technology equal $c_c = c_0 + p$.[51]

Firms can invest in an emission-free technology to produce G at carbon costs of zero. Investing implies that firms adopt new production processes within their existing production sites. As a result, the production capacity of the firms remains unaffected by an investment.[52] The investment decision is irreversible and induces investment costs as well as higher marginal production costs. We assume firms face heterogeneous investment costs, similar to the approach in Harstad (2012) or Requate and Unold (2003).[53] This heterogeneity may stem from several sources, e.g., because firms can adopt different technologies, have different access to resources, or have different R&D capacities. In our model, firms are ranked from low to high investment costs, such that they can be placed within an interval ranging from $[0, \chi_{max}]$.[54] We assume the firm-specific investment costs to be the product of the firm-specific position on the interval χ and a positive investment cost parameter c_i that is identical among firms. Hence, the investment costs of the firm positioned at χ equal $C_i(\chi) = \chi c_i$. Firms invest if they increase their profit by adopting the emission-free technology. Otherwise, they produce conventionally. We identify the firm which is indifferent between the two technologies by $\overline{\chi}$. As $C_i'(\chi) > 0$, all firms with $\chi \leq \overline{\chi}$ invest. In other words, $\overline{\chi}$ refers to the marginal firm investing in the emission-free technology. The position of a

[51] We discuss the implication of assuming constant marginal damage in chapter 5.5.

[52] This does not exclude market entry of new firms; however, we do not model entry or exit decisions explicitly, as adopting new processes in established installations is likely less costly then investing in new installations.

[53] Empirical evidence shows that firms differ with respect to their costs of investing in pollution abatement Blundell et al. (2020).

[54] χ_{max} represents the production capacity of all firms and is assumed to exceed the demand $Q(p_G)$ for all possible values of p_G.

firm on the interval χ not only defines the firm-specific investment costs but also corresponds to the cumulative production capacity of all firms facing investment costs lower than the respective firm. In consequence, $\overline{\chi}$ defines the emission-free production capacity. In the following, we refer to $\overline{\chi}$ interchangeably either as the emission-free production capacity or as the marginal firm.

Emission-free production has additional marginal production costs c_v. This technology may, for instance, require more expensive input factors compared to the conventional technology. Hence, the total marginal production costs of firms using the emission-free technology equal $c_f = c_0 + c_v$. In section 5.2 and 5.3, we assume the marginal production costs of the emission-free technology to be lower than the carbon price (i.e., $c_v < p$). We alleviate the assumption in section 5.4. Additionally, we adopt the normalization $c_0 = 0$. Considering investment and production costs, the profit of investing in the emission-free technology equals $\pi(\chi) = p_G - (c_0 + c_v + c_i\chi)$.

The regulator aims at maximizing the welfare resulting from the market for G. For this, the regulator can choose among the three different carbon pricing regimes. Firstly, she can opt for *Regulatory Flexibility* (short: *Flex*), in which she sets the carbon price flexibly after the investment decisions of the firms took place. Secondly, she can make a *Commitment* (short: *Com*) and commit to a carbon price before the investment takes place. The third option *CCfD* is a hybrid policy of offering CCfDs to the firms before the investments take place and setting the carbon price afterwards. The CCfD sets a strike price p_s that safeguards firms against carbon price volatility. If the carbon price, which realizes after the investments, is lower than the strike price, the regulator pays the difference $(p_s - p)$ to the firm. If the carbon price is higher than the strike price, firms have to pay the difference to the regulator.

Before introducing the sequence of actions, we discuss the model approach and its main assumptions. First, a price-elastic demand, a competitive market structure, and the provision of homogeneous goods resemble many industries for which CCfDs are proposed, e.g., steel and chemicals (e.g. European Commission, 2021f, Fernández, 2018, OECD, 2002). Second, these industries likely face a discrete, irreversible investment decision to decarbonize the production in combination with increased marginal production costs of the low-carbon technology. Currently, a switch of production processes from the coal- and coke-based blast furnace to hydrogen-based direct reduction is seen as the most promising way to decarbonize the primary steel sector (e.g. IEA, 2021). This switch in the production process induces a shift in input factors from coal to more expensive hydrogen (Vogl et al., 2018). Hence, our model captures many characteristics of industries, for which policymakers propose the use of CCfDs.

The agents in our model can take actions in four stages, namely the Early Policy stage t_1, the Investment stage t_2, the Late Policy stage t_3, and the Market Clearing stage t_4. Figure 5.1 depicts these stages. The sequence of actions differs between the carbon pricing regimes that we analyze in this paper. We subsequently discuss the agents' actions during the various stages of the game. As we derive the sub-game perfect Nash equilibrium by backward induction, we begin by presenting the last stage of the game.

		Firms	**Regulator**			**Social Planner**
			Com	*Flex*	*CCfD*	*Opt*
Early Policy	(t_1)		Sets p		Sets p_s	
Investment	(t_2)	Invest up to $\overline{\chi}$				Sets $\overline{\chi}$
Late Policy	(t_3)			Sets p	Sets p	Sets p
Market Clearing	(t_4)	$p_G^* = p$ and $Q(p_G^*) = Q(p)$				
	T					

Figure 5.1.: Sequence of actions in the different carbon pricing regimes.

Market Clearing stage: In t_4, the market clearing takes place. Firms produce the good with the respective technologies and serve the demand. In this stage, the carbon price p and the resulting emission-free production capacity $\overline{\chi}$ are already determined.

Late Policy stage: In t_3, the regulator sets the carbon price under *Regulatory Flexibility* and *CCfD*, given the previously determined production capacity of the emission-free technology.

Investment stage: In t_2, the firms decide whether to invest in the emission-free technology or not. Firms with $\chi \leq \overline{\chi}$ invest as they increase their profit by adopting the emission-free technology, while the others ($\chi > \overline{\chi}$) maintain the conventional technology.

Early Policy stage: In t_1, the regulator can take actions in two of the three carbon pricing regimes. Under *Commitment*, she announces and commits to a carbon price for the subsequent stages. Under *CCfD*, the regulator offers firms CCfDs and determines the strike price.

In contrast to the other stages, the market clearing in t_4 is independent of the carbon pricing regime, such that we present the result upfront. We assume the investment costs to be sufficiently high compared to the demand, such that investments in the emission-free capacity cannot supply the overall demand, i.e., $\overline{\chi} < Q(p_G)$. This assumption implies that the demand for the good is partially served by firms that invested in the emission-free technology and by firms producing conventionally.[55] As demand exceeds the emission-free production capacity and marginal production costs of the emission-free technology are lower than of the conventional technology, the latter sets the market price. Due to the normalization of $c_0 = 0$, the market price is defined by $p_G = p$ and the demand is equal to $Q(p_G) = Q(p)$, i.e., the carbon price fully determines the product price. Figure 5.2 illustrates the market clearing.

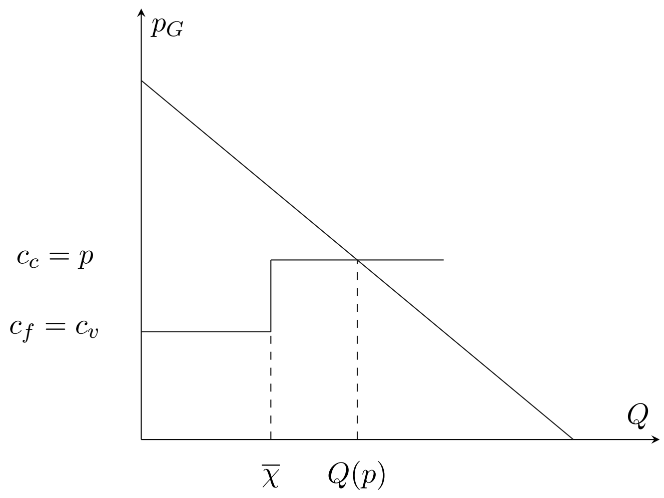


Figure 5.2.: Market clearing.

Firms producing the good with the conventional technology do not generate profits as marginal revenue equals marginal costs, which are constant. The marginal profit of production of the firms investing in the emission-free technology equals $p - c_v$. Together, the assumptions $\overline{\chi} < Q(p_G)$ and $c_v < p$ ensure that some firms will invest in the emission-free technology. The first assumption addresses the fixed investment costs and the second the variable costs of the emission-free technology. These assumptions also ensure that some firms continue producing conventionally. Section 5.5 discusses why CCfDs can only be beneficial in this setting.

To evaluate the carbon pricing regimes, we compare the respective outcomes to the social optimum (short: *Opt*). In this hypothetical benchmark, a social planner sets the socially optimal investment in t_2 and the carbon price level in t_3. The social planner's objective is, identical to the regulator, to maximize social welfare stemming from the market for the product G. Social welfare comprises four elements: 1) net consumer surplus (CS), 2) producer surplus, 3) environmental damage, and 4) policy costs/revenues from carbon pricing and the CCfD.

[55] We discuss this assumption in section 5.5, as it is crucial for the outcome of the market clearing and the resulting incentives to invest in the emission-free technology.

The producer surplus is defined as the margin between marginal revenue and marginal costs. It differs before and after the irreversible investment. Before the investment, i.e., in t_1 and t_2, the marginal costs comprise investment and marginal production costs. After the investment, i.e., in t_3 and t_4, the investment costs are sunk, such that the marginal costs only comprise the marginal production costs. Equation 5.1 displays the welfare before the investment takes place. The welfare representation after the investment takes place does not contain the investment costs $\int_0^{\overline{\chi}}(c_i z)dz$.

$$\begin{aligned}
\mathcal{W}^{Flex/Com/Opt} &= \underbrace{\int_p^{\infty} Q(z)dz}_{\substack{\text{consumer}\\\text{surplus}}} + \underbrace{\int_0^{\overline{\chi}} (p - c_v - c_i z)dz}_{\text{producer surplus}} - \underbrace{d\big[Q(p) - \overline{\chi}\big]}_{\substack{\text{environmental}\\\text{damage}}} + \underbrace{p\big[Q(p) - \overline{\chi})\big]}_{\substack{\text{revenues from}\\\text{carbon pricing}}} \\
\mathcal{W}^{CCfD} &= \underbrace{\int_p^{\infty} Q(z)dz}_{\substack{\text{consumer}\\\text{surplus}}} + \underbrace{\int_0^{\overline{\chi}} (p_s - c_v - c_i z)dz}_{\text{producer surplus}} - \underbrace{d\big[Q(p) - \overline{\chi}\big]}_{\substack{\text{environmental}\\\text{damage}}} + \underbrace{p\big[Q(p) - \overline{\chi})\big]}_{\substack{\text{revenues from}\\\text{carbon pricing}}} - \underbrace{(p_s - p)\overline{\chi}}_{\substack{\text{CCfD}\\\text{payment}}}
\end{aligned} \tag{5.1}$$

Payments arising from the CCfD do not affect the overall welfare as they only shift payments between firms and the regulator.[56] Hence, we can simplify welfare with and without CCfDs before investment to:

$$\mathcal{W} = \int_p^{\infty} Q(z)dz + (p - d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \tag{5.2}$$

This simplified representation illustrates that welfare can be grouped into two elements. On the one hand, welfare is defined by consumption, the associated environmental damage, and the carbon pricing revenue. On the other hand, welfare stems from the level of emission-free production capacity $\overline{\chi}$ and the related costs and benefits from abatement.

5.2.2. Policy ranking in the absence of risk

In the following, we derive the optimal emission-free production capacity $\overline{\chi}$ and the optimal carbon price p in the absence of risks (i.e., under perfect foresight) under the assumption of a social planner. The solution serves as a hypothetical benchmark for the three carbon pricing regimes. To solve the optimization of the

[56] Note that we do not assume shadow costs of public funds. We discuss this assumption in section 5.5.

social planner, we derive the first-order conditions of the welfare function:

$$\begin{aligned}
\max_{\overline{\chi},p} \mathcal{W} &= \int_p^{\infty} Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \\
\frac{\partial \mathcal{W}}{\partial \overline{\chi}} &= (d - c_v - c_i\overline{\chi}) \longrightarrow \overline{\chi}^{Opt} = \frac{d-c_v}{c_i} \\
\frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p-d) \longrightarrow p^{Opt} = d
\end{aligned} \tag{5.3}$$

The social planner chooses the emission-free production capacity such that the abatement costs (i.e., the investment and production costs) of the marginal firm ($\overline{\chi}^{Opt}$) equal the damage avoided by the investment in and the utilization of the emission-free technology. The optimal carbon price (p^{Opt}) equals the marginal damage, i.e., the Pigouvian tax level (Pigou, 1920), as the marginal unit of the good is produced with the conventional technology, associated with an environmental damage of d. With this carbon price, the social planner inhibits all consumption with a lower benefit than damage to society.

We provide the optimal solutions under the different carbon pricing regimes in D.1. We find that

Proposition 5.2.1. *In the absence of risk, all carbon pricing regimes reach the social optimum. In all regimes, the carbon price is equal to the marginal environmental damage of production, i.e., $p = d$. The marginal firm using the emission-free technology balances the marginal investment costs and the respective marginal benefit of abatement, i.e., $\overline{\chi} = {}^{(d-c_v)}/_{c_i}$.*

In the absence of risk, i.e., under perfect foresight, the optimization rationales in t_1 (before investing) and t_3 (after investing) regarding balancing the damage from carbon emission and the costs of abatement are identical. Therefore, it does not make a difference if the regulator commits to a carbon price before the firms invest or sets the carbon price flexibly afterward. Under all regimes, Pigouvian taxation is optimal. Hence, offering a CCfD in t_1 does not improve social welfare.

This result regarding the welfare ranking of carbon pricing regimes and, notably, CCfDs differs from Chiappinelli and Neuhoff (2020). In their model, firms also face an irreversible investment decision but behave strategically and influence the regulator's decision on the carbon price. Thereby, firms under-invest to induce higher carbon prices, leading to a hold-up problem. In this setting, CCfDs can alleviate the investment-hampering effect of flexible carbon prices and increase welfare. In contrast, firms do not have market power in our model and cannot affect the regulator's carbon pricing decision. Hence, it does not make a difference if the firms invest before or after the regulator sets the carbon price under perfect foresight.

Proof. We provide the proof of Proposition 5.2.1 in D.1. ■

5.3. Carbon pricing regimes in the presence of risk

In this section, we analyze the impact of damage and variable cost risk on the welfare ranking of the carbon pricing regimes in the presence of risk aversion.

5.3.1. Model framework in the presence of risk and socially optimal production

We integrate risk into the model by redefining the marginal environmental damage and the variable production costs of the emission-free technology from the model introduced in section 5.2.1 as random variables D and C_v. Both random variables realize after the firms invest in abatement (t_2), but before the late policy stage (t_3) and the market clearing (t_4). We denote the realization of D and C_v by $\hat{d}$ and $\hat{c_v}$. In this section, we assume the production with the emission-free technology to be socially optimal under all circumstances, i.e., the environmental damage is always larger than the variable costs of abatement $P(D > C_v) = 1$. For this assumption to hold, we define the random variables to follow a truncated normal distribution, i.e., $D \sim TN(\mu_D, \sigma_D^2, \underline{\theta_D}, \overline{\theta_D})$ and $C_v \sim TN(\mu_{C_v}, \sigma_{C_v}^2, \underline{\theta_{C_v}}, \overline{\theta_{C_v}})$ with $\underline{\theta_D} > \overline{\theta_{C_v}}$, where μ denotes the mean value, σ^2 the variance and $\underline{\theta}$ and $\overline{\theta}$ the lower and upper limit of the distribution, respectively. Hence, the lowest possible damage is larger than the highest possible realization of variable costs.[57] As in section 5.2, we assume $\chi < Q(p(d))$, such that for all $\hat{d} \in D$ the total demand in the market exceeds the emission-free production capacity.

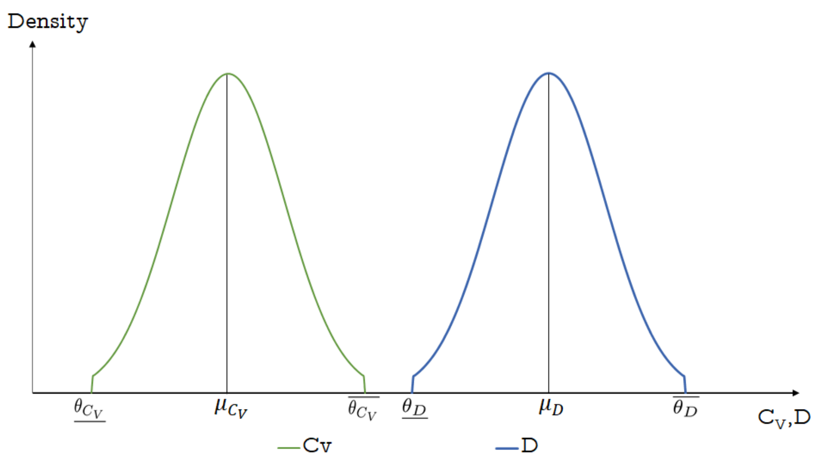


Figure 5.3.: Density of D and C_v following a truncated normal distribution with $P(C_v > D) = 0$.

[57] We assess a setting in which the social costs of damage are potentially smaller than the variable costs of abatement, i.e., $P(D > C_v) < 1$, in section 5.4 by assuming an non-truncated normal distribution.

We assume that firms are risk averse, facing a utility that is exponential in profits. Whether or not risk aversion is a real-world phenomenon for firms and how it manifests in actions is debated within the broad literature of economics and the context of energy and environmental economics (Meunier, 2013). Diamond (1978) argues that even if markets were incomplete, firms should act as if they were risk neutral, and shareholders could hedge their risks at the capital markets. However, there are several reasons why firms may act aversely to risk (see e.g. Banal-Estañol and Ottaviani (2006) for a review). These reasons include non-diversified owners, liquidity constraints, costly financial distress, and nonlinear tax systems. Additionally, and independently of the owners' risk aversion, the delegation of control to a risk-averse manager paid based on the firm's performance may cause the firm to behave in a risk-averse manner.

How the firms' risk aversion can be modelled depends on the distributional assumptions of the underlying risks. Markowitz (1952) show that for non-truncated normally distributed profits, the mean-variance utility could express firms' optimization rationale. However, this simplification is not appropriate for our model in which the distribution of firms' profits is truncated due to distributional assumptions on damage and variable cost risk. Norgaard and Killeen (1980) show that the optimization rationale of an agent facing an exponential utility and truncated normally distributed profits can be approximated by a mean-standard deviation decision rule containing a risk aversion parameter λ.[58] We apply this approximation by using a mean-standard deviation utility in our model. Firms invest in the emission-free technology if their expected utility is positive. The expected utility of the marginal firm investing in the emission-free technology is equal to zero:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= \mu_{\pi}(\overline{\chi}) - \lambda\sigma_{\pi}(\overline{\chi}) \\ &= (\mu_p - \mu_{C_v} - c_i\overline{\chi}) - \lambda\sigma_{p,C_v} \\ &= 0 \end{aligned} \tag{5.4}$$

In contrast to the firms' risk aversion, we assume the regulator to be risk neutral. There are several reasons why environmental regulation is determined on a risk-neutral basis (see e.g. Kaufman (2014) for an extensive review). In the context of public economics, Arrow and Lind (1970) argue that with a sufficiently large population, the risk premiums converge to zero because they can be spread out among constituents. Fisher (1973) discusses the principles of Arrow and Lind

[58] In the context of energy and environmental economics, Alexander and Moran (2013) apply this approach to assess the impact of perennial energy crops income variability on the crop selection of risk-averse farmers.

in the context of risks stemming from environmental externalities. [59] Hence, we assume the regulator to maximize the expected welfare:

$$E[\mathcal{W}] = E\bigg[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz\bigg] \tag{5.5}$$

5.3.2. Policy ranking with damage risk

In the following, we focus on damage risk and neglect the risk of the variable production costs. Therefore, we set $\mu_{C_v} = c_v$ with $\sigma^2_{C_v} = 0$. We derive and compare the outcomes of the three carbon pricing regimes in terms of the emission-free production capacity $\overline{\chi}$ and carbon price p in the presence of damage risk. We contrast the three regimes to the social optimum and conclude that

Proposition 5.3.1. *In the presence of damage risk and firms' risk aversion, only the hybrid policy of offering a CCfD and setting the carbon price flexibly yields a socially optimal level of p and $\overline{\chi}$. A pure carbon pricing regime reaches either a socially optimal carbon price through allowing for flexibility or optimal investment through early commitment.*

As the valuation of environmental damage is not known before investing (t_1), while it is known after investing (t_3), the timing of the carbon pricing regimes changes the carbon prices and the resulting market outcomes. When setting the carbon price flexibly in t_3, all relevant information is available for the regulator. Hence, the *Regulatory Flexibility* regime results in the socially optimal carbon price for the market clearing. However, in this regime, firms face a risk regarding their revenues. Due to their risk aversion, firms consequently invest less than socially optimal. When committing to a carbon price in t_1, the regulator cannot take into account the information becoming available in t_3. Hence, the carbon price under *Commitment* is ex-post either too high or too low. However, the carbon price commitment incentivizes socially optimal investments. It accounts for the risk in the valuation of environmental damage; that is, the firms and the regulator face the same problem. Offering a CCfD removes the impact of damage risk for the firms and enables socially optimal investments. Furthermore, socially optimal consumption is reached as the regulator sets the carbon price in t_3, having complete information on the damage valuation.

Proof. For the proof of proposition 5.3.1, we compare the socially optimal carbon price and emission-free production capacity to the three carbon pricing regimes.

[59] Besides the risk neutrality of the regulator, we assume that her welfare maximization is also not affected by the firms' risk aversion. This corresponds to the concept of the literature on non-welfarist taxation, which is common practice in public economics (e.g. Heutel (2019), Kanbur et al. (2006)). In essence, the regulator's *ignorance* of the risk-averse utility of the firms can stem from either paternalistic behaviour or an insufficiently large proportion of the firms on the market.

D.2 presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 5.3.1.

Social optimum

In the social optimum, the social planner sets the carbon price p after the actual environmental damage revealed. Following the rationale of the risk-free setting, the socially optimal carbon price equals the realized marginal damage, i.e., $p^{Opt} = \hat{d}$. As the social planner knows the actual damage level when setting the carbon price, the damage risk does not impact her decision.

In contrast, investments are due before the actual damage reveals. Hence, the social planner must set the emission-free production capacity $\overline{\chi}$ in the presence of damage risk. The social planner sets $\overline{\chi}^{Opt}$ such that it maximizes the expected welfare gain from abatement investments.

$$\overline{\chi}^{Opt} = \frac{\mu_D - c_v}{c_i} \tag{5.6}$$

The emission-free production capacity balances the expected benefit of abatement, i.e., the expectation of the avoided environmental damage and the abatement costs, consisting of variable production costs and investment costs.

Regulatory flexibility

Similar to the social planner case, the regulator sets the carbon price after the actual damage revealed when she chooses *Regulatory Flexibility.* As the regulator and the social planner have the same objective function, both settings result in a carbon price at $p^{Flex} = p^{Opt} = \hat{d}$, i.e. the Pigouvian tax level.

In t_2, the firms choose to invest if their expected utility is positive, anticipating the carbon price set by the regulator in the following stage. However, the price is stochastic to firms, as it depends on the realized damage.

$$\overline{\chi}^{Flex} = \frac{\mu_{p^{Flex}} - c_v - \lambda\sigma_{p^{Flex}}}{c_i} = \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} \tag{5.7}$$

Unlike in the case of a (risk-neutral) social planner, firms not only account for the expected revenues and costs of abatement but also consider a risk term stemming from the abatement revenue risk. This risk term reduces the firms' expected utility and consequently the emission-free production capacity, as firms aim to avoid situations where their investments are unprofitable. The dampening effect of risk on investments increases with the volatility of expected carbon prices and the firms' risk aversion.

Commitment

Under *Commitment*, the firms' investment rationale is based on the carbon price known at the time of taking their decision:

$$\overline{\chi}^{Com} = \frac{p^{Com} - c_v}{c_i} \tag{5.8}$$

Following the intuition of the setting without risk, those firms invest which increase their profit by adopting the emission-free technology. As revenues are not subject to risk, the firms' risk aversion does not impact their investment decisions in t_2 and the resulting emission-free technology balances the marginal revenue and the marginal costs of abatement.

In t_1, the regulator sets the carbon price maximizing expected welfare and taking into account that firms solely invest if the investment is profitable. As a result, the regulator sets the carbon price to $p^{Com} = \mu_D$, i.e., the expected Piguvian tax level. Substituting the optimal carbon price p^{Com} into (5.8) yields $\overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i}$, which is equal to the solution of the social planner. However, the carbon price to which the regulator commits herself in t_1 is ex-post not optimal. If the revealed damage is greater than expected, the carbon price is too low, and vice versa.

CCfD

When the regulator can offer the firms a CCfD, the regulator faces the same objective function for setting the carbon price in t_3 as under *Regulatory Flexibility*. Hence, she chooses the Pigouvian tax level $p^{CCfD} = p^{Flex} = p^{Opt} = \hat{d}$.

In t_2, the firms' problem is identical to the one under *Commitment*. Here, the firms receive the strike price:

$$\overline{\chi}^{CCfD} = \frac{p_s - c_v}{c_i} \tag{5.9}$$

The rationale for investments is the same as without risk: Firms invest in the emission-free technology if it increases their profits. In t_1, the regulator chooses the strike price that maximizes expected social welfare. She accounts for the firms' reaction function to the announced strike price and faces damage risk. The resulting strike price equals the expected marginal damage, i.e., $p_s = \mu_D$. By substituting p_s in (5.9), we see that under a *CCfD* regime, the emission-free production capacity equals the one under *Com* (and the social planner), i.e., $\overline{\chi}^{CCfD} = \overline{\chi}^{Com} = \overline{\chi}^{Opt}$). ■

Welfare Comparison

We calculate and compare the ex-ante social welfare in the different carbon pricing regimes in terms of welfare.[60] We find that:

$$E[\mathcal{W}_{\sigma_D}^{Opt}] = E[\mathcal{W}_{\sigma_D}^{CCfD}] \geq E[\mathcal{W}_{\sigma_D}^{Com}] \lesseqgtr E[\mathcal{W}_{\sigma_D}^{Flex}] \tag{5.10}$$

First, the carbon price and the emission-free production capacity are identical in the social optimum and the *CCfD* regime. Consequently, the *CCfD* regime results in the social optimum.

Second, we compare offering a CCfD against *Regulatory Flexibility* and *Commitment*. While the *CCfD* regime achieves the socially optimal emission-free production capacity, investments in *Flex* are lower. As the expected welfare increases in χ as long as $\chi \leq \overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$, the welfare under the *Flex* regime is lower than the social optimum or offering a CCfD. The welfare loss increases in the firms' risk aversion and the standard deviation of environmental damage. However, if firms are risk neutral, the *Flex* regime reaches the socially optimal emission-free production capacity. Figure 5.4i shows these results numerically. Note that these parameter values are illustrative and do not correspond to empirical estimates.[61] In contrast to the case of *Regulatory Flexibility*, the policy regimes *Commitment* and *CCfD* both result in the socially optimal emission-free production capacity. However, these regimes differ concerning the carbon price level and the resulting utility from consumer surplus. Under the *Com* and *CCfD* regimes, consumers bear the same carbon prices in expectation. However, the consumer surplus is a convex function of the respective carbon price. I.e., a higher carbon price decreases the consumer surplus less than an equivalently lower carbon price would lead to an increase of the consumer surplus.[62] Hence, the difference in expected consumer surplus is positive, i.e., $E[\int_{p^{CCfD}}^{\infty} Q(z)dz] > \int_{p^{Com}}^{\infty} Q(z)dz$. With an increase in demand elasticity, the difference in consumer surplus of the *Com* and *CCfD* regimes increases. Therefore, the greater the demand elasticity, the higher the loss in ex-ante welfare arising from not setting the carbon price according to the actual marginal damage under *Com*. We illustrate this finding numerically in Figure 5.4ii.

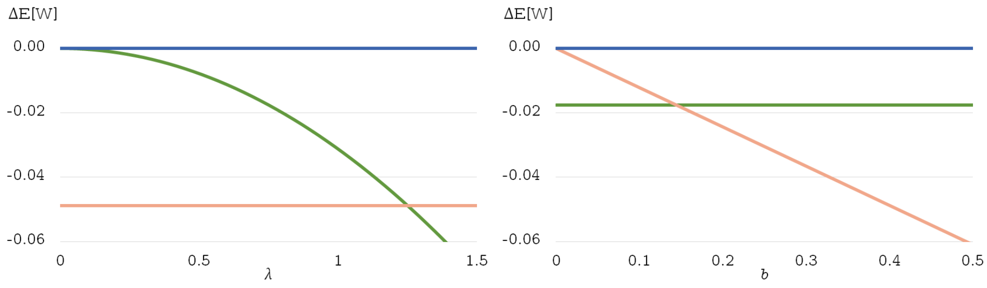
Third, it is unclear whether *Com* or *Flex* is welfare superior. *Flex* results in socially optimal carbon pricing, while *Com* allows for socially optimal emission-free production capacity. Which regime is welfare superior depends on the relevance of the two variables. In case of damage risk, setting a flexible carbon price is

[60] The subscript σ_D represents the welfare in the presence of damage risk.

[61] Both Figure 5.4i and Figure 5.4ii share the parameters regarding the distribution of the environmental damage $D \sim TN(\mu_D = 4, \sigma_D^2 = 0.25, \underline{\theta_D} = 2.5, \overline{\theta_D} = 5.5)$ and the cost parameters of the emission-free technology $c_v = 2$ and $c_i = 4$.

[62] This relation is also known as the Jensen gap stemming from Jensen's inequality.

welfare superior to *Com* if demand elasticity is sufficiently high and the share of emission-free production is sufficiently low. The same holds vice versa for *Com*.



(i) Effect of risk aversion

(ii) Effect of elasticity

Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $Q(p) = 5 - 0.4p$ and (b): $\lambda = 0.75$, $Q(p) = 5 - bp$ with $b \in (0, 0.5]$.

Figure 5.4.: Difference in welfare compared to social optimum in the presence of damage risk.

5.3.3. Policy ranking with variable cost risk

In this section, we focus on variable cost risk and set $\mu_D = d$ with $\sigma_D^2 = 0$. We derive the outcomes of the three carbon pricing regimes in terms of emission-free production capacity $\overline{\chi}$ and carbon price p when the firms do not know the variable costs of the emission-free technology when investing. We contrast the three regimes with the social optimum and conclude that

Proposition 5.3.2. *In the presence of variable cost risk, only the hybrid policy of offering a CCfD and setting the carbon price flexibly yields a socially optimal level of p and $\overline{\chi}$. A pure carbon price in a regime with Regulatory Flexibility reaches a socially optimal carbon price p but falls short of the socially optimal emission-free production capacity $\overline{\chi}$. Commitment reaches neither the socially optimal level of p nor $\overline{\chi}$.*

When firms face a variable abatement costs risk, risk aversion reduces the utility from investing in the emission-free production technology. Depending on the carbon pricing regime, the regulator can mitigate this effect. The regulator can encourage firms to increase investments by setting the carbon price above the Pigouvian tax level when committing to a carbon price. However, the price increase results in inefficient consumption levels. Hence, the regulator faces a trade-off between high consumer surplus and low environmental damage, resulting in a deviation from the social optimum. When the regulator can offer a CCfD in addition to a carbon price, she does not face this trade-off. Instead, the regulator can offer a CCfD, which sufficiently compensates firms for facing risk regarding their revenue and enable socially optimal investments. Furthermore, the regulator achieves the socially optimal consumption level. She can set the carbon price to the Pigouvian tax level, indicating the benefit of having two instruments for different objectives. If the regulator cannot offer a CCfD and sets the carbon price flexibly, the regulator achieves the socially optimal consumption level but cannot alter the firms' investment decisions. Consequently, fewer firms invest than socially optimal.

Proof. For the proof of proposition 5.3.2, we compare the socially optimal carbon price and emission-free production capacity to the three carbon pricing regimes. D.3 presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 5.3.2.

Social optimum

In the social optimum, the social planner maximizes welfare by setting the carbon price p^{Opt} after the level of variable costs revealed. She chooses the Pigouvian tax level $p^{Opt} = d$, which equals the social marginal costs of production.

The social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ under risk such that it maximizes the expected welfare. The emission-free production capacity balances the marginal benefit and marginal costs from abatement. The optimization rationale resembles the one under damage risk. However, in this case, not the benefit of emission-free production but its costs are subject to risk:

$$\overline{\chi}^{Opt} = \frac{d - \mu_{C_v}}{c_i} \tag{5.11}$$

Regulatory flexibility

Under *Regulatory Flexibility*, the regulator faces the same optimization problem as the social planner. Hence, she sets the carbon price to the Pigouvian tax level $p^{Flex} = p^{Opt} = d$.

In t_2, firms invest in the emission-free technology if the investment increases the expected utility of the firm. For this, the firms anticipate the Pigouvian tax. As firms are risk averse, the firms' utility decreases in the level of risk and risk aversion. The resulting emission-free production capacity equals:

$$\overline{\chi}^{Flex} = \frac{p^{Flex} - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} = \frac{d - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{5.12}$$

The emission-free production capacity falls short of the social optimum in case of risk aversion ($\lambda > 0$). The shortfall increases with an increasing level of risk and risk aversion.

Commitment

Under *Commitment*, in t_2, firms choose to invest given the announced carbon price level. As in the case of *Regulatory Flexibility*, firms invest if they generate a positive expected utility, such that the emission-free production capacity equals:

$$\overline{\chi}^{Com} = \frac{p - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{5.13}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts firms' investment decisions and the consumer surplus. These two effects result in a trade-off which we can express as:

$$\frac{p-d}{p} = \frac{1}{\epsilon(p)} \frac{\partial\overline{\chi}^{Com}(p)}{\partial p} \frac{1}{Q(p)} (d - c_i\overline{\chi}^{Com}(p) - \mu_{C_v}), \tag{5.14}$$

where $\epsilon(p) = -\frac{\partial Q(p)}{\partial p}\frac{p}{Q(p)}$ is the elasticity of demand.

The resulting carbon price is higher than d, which we show in D.3. In fact, the optimal carbon price under commitment p^{Com} ranges from $[d, d+\lambda\sigma_{C_v}]$, depending on the configuration of parameters. Hence, the regulator sets a carbon price above the social marginal costs of the conventional technology, i.e. d, and the carbon price is higher than in the social optimum. The solution is a modified version of the Ramsey formula for monopolistic price setting under elastic demand (Höffler, 2006, Laffont and Tirole, 1996). The regulator increases the carbon price above the socially optimal level to encourage investments. This price mark-up is proportionate to the inverse price elasticity of demand and the marginal benefit from increased investments. The marginal benefit arises from the marginal increase in the share of emission-free production, i.e., $\frac{\partial\overline{\chi}^{Com}(p)}{\partial p}\frac{1}{Q(p)}$, and the benefit of the marginal emission-free production, i.e., $d - c_i\overline{\chi}^{Com}(p) - \mu_{C_v}$. In other words, the regulator balances the loss in consumer surplus and the abatement benefits.

The trade-off under *Com* with variable cost risk is different from the case with damage risk: With damage risk, the regulator commits to a carbon price that will be sub-optimal ex-post. By committing to a carbon price, the regulator takes up the firms' risk, mitigating the negative effect of the firms' risk aversion on social welfare. With cost risk, the regulator cannot take away the firms' risk, but she can compensate the firms for taking the risk. By committing to a carbon price that includes a premium, she incentivizes more investments. However, this price increase has the downside of a loss in consumer surplus and, in consequence, neither consumption nor investments are socially optimal. If demand was fully inelastic, i.e., $Q'(p) = 0$, the trade-off would diminish. The regulator would set the carbon price such that she fully compensates the firms for their profit risk, i.e. $d + \lambda\sigma_{C_v}$.

CCfD

When the regulator can offer firms a CCfD in t_1, she sets the carbon price in t_3 after the actual variable costs revealed and firms invested in the emission-free technology. Her optimization problem is the same as under *Regulatory Flexibility* and the social optimum. Hence, $p^{CCfD} = d$.

In t_2, the firms' optimization rationale is the same as under the *Commitment*, only that they face a strike price instead of the carbon price.

$$\overline{\chi}^{CCfD} = \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \tag{5.15}$$

In t_1, the regulator chooses a strike price that maximizes expected social welfare and accounts for the firms' reaction to the strike price.

$$p_s = d + \lambda\sigma_{C_v} \tag{5.16}$$

In contrast to the previous cases, the regulator sets the strike price above the expected benefit of abatement. By substituting p_s^{CCfD} in (5.15), we see that under a *CCfD* regime, the emission-free production capacity equals the choice of the social planner, i.e., $\overline{\chi}^{CCfD} = \overline{\chi}^{Opt}$. The mark-up $\lambda\sigma_{C_v}$ of the strike price compensates firms for taking the risk. The strike price equals the upper limit of the carbon price under *Commitment*, i.e., the level of p^{Com} with fully inelastic demand. As the strike price does not affect the consumer surplus, the regulator can fully assume the firms' risk. In the absence of risk aversion, the regulator sets the strike price at the level of marginal damage. ■

Welfare Comparison

This subsection compares the ex-ante social welfare of the different carbon pricing regimes to determine which regime is socially optimal in an environment with risk regarding variable costs. We see that offering a CCfD yields the social optimum, while the other regimes fall short of it. Under *Commitment*, the carbon price is too high and the emission-free production capacity too low. With *Regulatory Flexibility*, the carbon price is socially optimal, but the emission-free production capacity is too low. We find that:

$$E[\mathcal{W}^{Opt}_{\sigma_{C_v}}] = E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Com}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Flex}_{\sigma_{C_v}}] \tag{5.17}$$

First, we compare the expected welfare in *CCfD* with the one the social planner obtains. As both the carbon price and the emission-free production capacity are identical, the *CCfD* regime results in the social optimum.

Second, we find that welfare in *Flex* falls short of the benchmark if firms are risk averse. Like in the case of damage risk, this arises due to too low investments.

With increasing risk aversion, the shortfall of investments and welfare increases - a finding that can also be observed numerically in Figure 5.5i.[63]

Third, we find that welfare under *Commitment* falls short of the social optimum but is superior to *Regulatory Flexibility*. The shortfall in welfare arises as the *Com* regime reaches neither the socially optimal carbon price nor the socially optimal emission-free production capacity. The welfare superiority of *Com* compared to *Flex* emerges as the regulator can influence not only the market size but also the investments by setting the carbon price early. In contrast to the damage risk case, there is no disadvantage from setting the carbon price early as the realization of the damage is known in t_1. When deciding on a carbon price under *Com*, the regulator balances the welfare gain from increased abatement arising from a higher carbon price against the welfare loss from decreased consumption. With an increasing elasticity of demand, e.g., due to an increasing slope of a linear demand function, the welfare loss from setting a higher carbon price increases. Hence, the higher the elasticity, the less the carbon price is increased compared to p^{Flex} by the regulator. In consequence, the relative advantage of *Com* compared to *Flex* decreases with increasing demand elasticity. Figure 5.5ii displays the finding numerically. The analytical proof showing the welfare of *Com* is superior to *Flex* can be found in D.3.

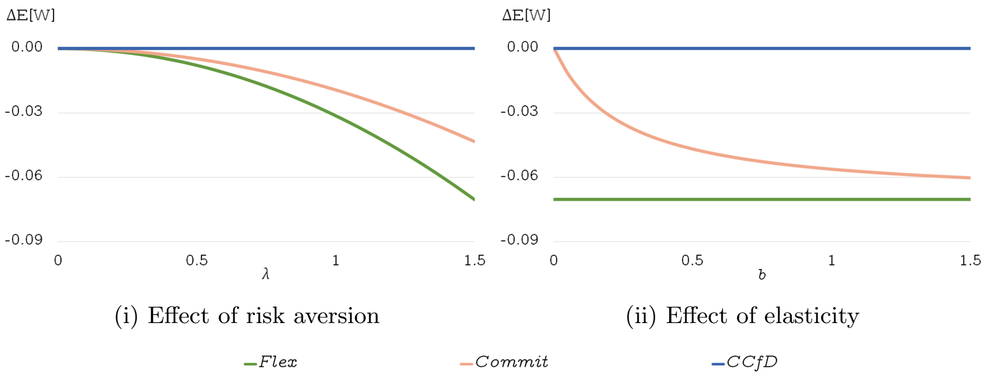


Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $Q(p) = 5 - 0.4p$ and (b): $\lambda = 1.5$, $Q(p) = 5 - bp$ with $b \in (0, 1.5]$.

Figure 5.5.: Difference in welfare compared to social optimum in the presence of cost risk.

[63] Both, Figure 5.5i and Figure 5.5ii, share the parameters regrading the distribution of the environmental damage and the costs related to the emission-free technology of Figure 5.4. The chosen parameter values are illustrative and do not correspond to empirical estimates.

5.4. Carbon pricing regimes with potentially socially not optimal production

In the previous section, we focused on the effects of different carbon pricing regimes in settings in which the production of the emission-free technology is always socially optimal in t_4, i.e., the variable costs of abatement are ex-post lower than the marginal environmental damage. In this section, we alleviate this assumption and allow for situations in which emission-free production may not be socially optimal.

5.4.1. Model framework in the presence of risk and socially not optimal production

To allow for situations in which the production of the emission-free technology is welfare reducing, we assume the environmental damage to be normally distributed instead of truncated normally distributed. That means there is a positive probability that variable costs exceed the realized damage, i.e. $P(C_V > D) > 0$ (see Figure 5.6).[64] We denote the cumulative distribution and probability density functions of D as $F_D(.)$ and $f_D(.)$. To keep investment in abatement ex-ante socially optimal in all cases, we maintain the assumption that $\mu_D > \mu_{C_V}$.

To emphasize the impact of potentially welfare-reducing production on the different carbon pricing regimes, we assume firms to be risk neutral when analyzing the problem analytically (section 5.4.2). As the three carbon pricing regimes yield the same outcome in the variable cost risk case if firms are risk neutral (see section 5.3.3), we focus on the damage risk case.[65] Hence, we set $\mu_{C_V} = c_v$ with $\sigma^2_{C_V} = 0$ in the following. Being risk neutral, firms invest if their expected profits are positive, i.e., $E[\pi(\chi)] > 0$. To assess the combined effect of potentially welfare-reducing production and risk aversion, we analyze the model numerically in section 5.4.3.

[64] The assumption of an untruncated normal distribution implies that $\chi < Q(p(d)$ cannot hold for all $\hat{d} \in D$. Instead, we can almost ensure that the emission-free capacity cannot cover the total demand by assuming $P(Q(p(d)) < \chi) \to 0$, such that the probability of this case is infinitesimally small and can be neglected.

[65] D.5 shows that all carbon pricing regimes yield the social optimum if risk stems from variable costs and production is potentially welfare reducing.

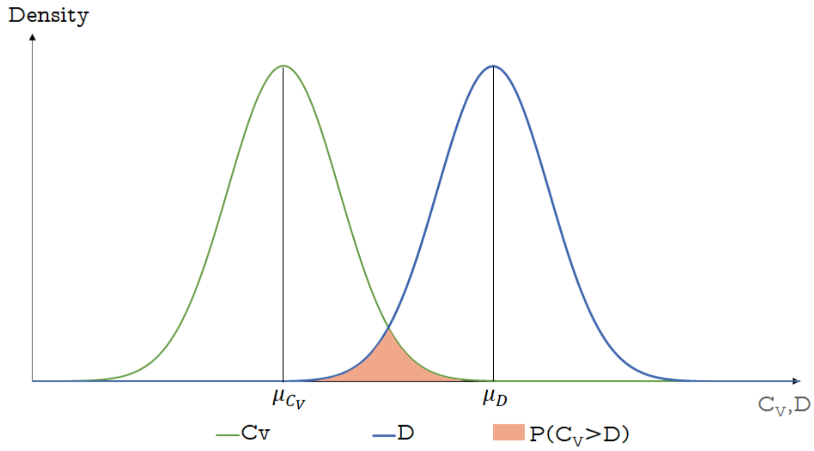


Figure 5.6.: Density of normally distributed D and C_V with $P(C_V > D) > 0$.

Due to the adjusted assumptions on the distribution of damage and costs, the carbon price applied in t_4 may be smaller than the variable costs, such that firms may not produce.[66] Firms may decide not to produce even if they invested in the emission-free technology as investment costs are sunk. The profit function can be defined as:

$$\pi(\chi) = \begin{cases} p - c_v - c_i\overline{\chi} & \text{if } c_v \leq p \\ -c_i\overline{\chi} & \text{else} \end{cases} \tag{5.18}$$

Like in section 5.3, we assume the regulator to be risk neutral. Hence, she maximizes the expected social welfare. As firms only produce if the carbon price exceeds the variable costs, welfare in t_4 is given by:

$$\mathcal{W} = \begin{cases} \int_p^\infty Q(z)dz + (p - \hat{d})Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz, & \text{if } c_v \leq p \\ \int_p^\infty Q(z)dz + (p - \hat{d})Q(p) - \int_0^{\overline{\chi}}(c_i z)dz, & \text{else} \end{cases} \tag{5.19}$$

5.4.2. Policy ranking with damage risk

This section analytically assess the different carbon pricing regimes when the emission-free production is potentially welfare reducing in a setting with damage risk and risk-neutral firms. We derive the outcomes of the three carbon pricing regimes regarding emission-free production capacity $\overline{\chi}$ and carbon price p. We contrast the three regimes to the social optimum and conclude that

Proposition 5.4.1. *In the presence of damage risk, potentially welfare-reducing production and risk-neutral firms, only setting a carbon price flexibly yield a socially optimal level of p and $\overline{\chi}$. Offering a CCfD or committing to a carbon*

[66]In section 5.3.2, the realized carbon price by assumption is higher than the marginal costs of production, such that firms produce for any realization of damage and costs.

price falls short of the social optimum, as these regimes safeguard emission-free production even if it is ex-post socially not optimal.

Under *Regulatory Flexibility*, the regulator can react flexibly to the actual environmental damage and sets the socially optimal Pigouvian tax level. Concurrently, as firms are risk neutral, investments are not hampered by the risk in profits. Hence, in *Flex*, the emission-free production capacity is socially optimal. In contrast, if the regulator offers a CCfD or commits to a carbon price, the firms' production decision is independent of the actual environmental damage. Hence, these regimes safeguard emission-free production even if it is ex-post socially not optimal. Although the regulator anticipates this effect and, in the *CCfD* regime, lowers the strike price, she cannot reach the social optimum. In addition to the welfare-reducing production level, committing to a carbon price early on also sets the carbon price for consumers, which is ex-post socially not optimal. As in the previous section, this socially not optimal carbon price level additionally lowers welfare.

Proof. For the proof of proposition 5.4.1, we compare the socially optimal carbon price and the emission-free production capacity to the three carbon pricing regimes. D.4 presents a complete derivation of the respective optimal solutions. In the following, we provide the main results and the intuition behind the finding in proposition 5.4.1. ■

Social optimum

In t_3, the social planner sets the carbon price p^{Opt} when the level of damage revealed. She optimizes (5.19), anticipating that her choice of the carbon price impacts the production of the emission-free technology. Irrespective of the production decision, the social planner sets the carbon price equal to the actual environmental damage, i.e., the Pigouvian tax level $p^{Opt} = \hat{d}$. Hence, whether firms that invested in the emission-free technology in t_2 produce in t_4 or not depends on the realization of marginal environmental damage.

In t_2, the social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ to maximize expected welfare. She considers the cases in which production of the emission-free technology may not be socially optimal, i.e., $c_v > \hat{d}$. Thereby, she knows that irrespective of the investment decision, firms will only produce if the realized damage is greater than the marginal variable costs of abatement. In the social optimum, she sets the emission-free production capacity to:

$$\overline{\chi}^{Opt} = \frac{\int_{c_v}^{\infty}(z - c_v) f_D(z) dz}{c_i} \tag{5.20}$$

The solution balances the expected benefit of abatement with its investment costs. The expected benefit of abatement is equal to the benefit from reduced environmental damage minus variable costs weighted by its probability of realization represented by the integral over the distribution function. The integral is limited to c_v as there is no emission-free production for $c_v > \hat{d}$.

Regulatory flexibility

Under *Regulatory Flexibility*, the regulator sets the carbon price after the actual damage revealed. Hence, in t_3, the regulator faces the same optimization problem as the social planner, such that $p^{Flex} = p^{Opt} = \hat{d}$.

Sunk investment costs from t_2 or whether the emission-free technology produces or not in t_4 are irrelevant for the regulator's decision.

In t_2, firms choose to invest if their expected utility is positive, anticipating that the Pigouvian carbon tax depends on the damage level that is not yet revealed.

The firms anticipate that they will only produce if the damage (and the respective carbon price) is large enough, i.e., $c_v \leq \hat{d}$. Thereby, the marginal firm investing in the emission-free technology is defined by

$$\overline{\chi}^{Flex} = \frac{\int_{c_v}^{\infty}(z - c_v) f_D(z) dz}{c_i} \tag{5.21}$$

In the absence of risk aversion, the investment rationales of firms and the social planner are aligned, such that *Flex* reaches the social optimum. This result extends the findings from sections 5.3.2 and 5.3.3 with $\lambda = 0$ to the case in which emission-free production can be ex-post welfare reducing.

Commitment

Under *Commitment*, firms choose to invest in the emission-free technology in t_2 given the announced carbon price level. The investment decisions are identical to those under *Regulatory Flexibility*, only that the firms know the carbon price when making their decision. Hence, the marginal firm investing in the emission-free technology is characterized by

$$\overline{\chi}^{Com} = \begin{cases} \frac{p^{Com} - c_v}{c_i} & \text{for } c_v \leq p \\ 0 & \text{else} \end{cases} \tag{5.22}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision. She chooses a carbon price equal to the expected environmental damage, i.e., $p^{Com} = \mu_D$. As in section 5.3.2 the carbon price is either too high or too low. By assumption, the expected damage is greater than the variable costs, i.e., $\mu_D > c_v$, which implies that investments and production occur. In cases where $\hat{d} < c_v$, the emission-free technology should not produce but does so in response to a too high carbon price. Furthermore, plugging in p^{Com} in (5.22) and subtracting the socially optimal investment level shows that the investment level under *Com* falls short of the social optimum:

$$\begin{aligned}\overline{\chi}^{Com} - \overline{\chi}^{Opt} &= \frac{\int_{-\infty}^{\infty}(z-c_v)f_D(z)dz}{c_i} - \frac{\int_{c_v}^{\infty}(z-c_v)f_D(z)dz}{c_i} \\ &= \frac{\int_{-\infty}^{c_v}(z-c_v)f_D(z)dz}{c_i} \\ &\leq 0\end{aligned} \tag{5.23}$$

This result shows that the regulator incentivizes less investments than socially optimal in order to limit the welfare loss arising from potentially welfare-reducing production.

CCfD

When the regulator offers a CCfD in t_1, the optimization rationale in t_3 is the same as in the social optimum and under *Regulatory Flexibility* (5.19). The solution yields the socially optimal Pigouvian tax level

$$p^{CCfD} = p^{Opt} = p^{Flex} = \hat{d} \tag{5.24}$$

In t_2, the investment decision of firms is identical to the rationale under the other regimes and hence:

$$\overline{\chi}^{CCfD} = \begin{cases} \frac{p_s - c_v}{c_i}, & \text{for } c_v \leq p_s \\ 0, & \text{else} \end{cases} \tag{5.25}$$

If the strike price, i.e., the firms' marginal revenue, is larger than their variable costs, they invest in the emission-free technology. Otherwise, it is not worthwhile for firms to enter a CCfD and invest.

In t_1, the regulator chooses a strike price that maximizes social welfare. She accounts for the firms' reaction to the strike price.

$$p_s = \begin{cases} \mu_D, & \text{for } c_v \leq \mu_D \\ 0 \leq p_s < c_v, & \text{else} \end{cases} \tag{5.26}$$

By assumption $\mu_D > c_v$ holds. Hence, only the first case materializes, and the regulator offers a CCfD that incentivizes investments and production. The resulting emission-free production capacity and production coincide with the one under *Commitment*. Hence, socially not optimal production occurs in those cases were $\hat{d} < c_v$. Furthermore, less investments than socially optimal are incentivized

($\overline{\chi}^{CCfD} = \overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i} < \overline{\chi}^{Opt}$) in order to limit the negative welfare effects of socially not optimal production.

Welfare comparison

We now compare the welfare of the three carbon pricing regimes in a setting of damage risk, risk-neutral firms, and potentially welfare-reducing emission-free production. *Regulatory Flexibility* yields both the socially optimal emission-free production capacity and carbon price. Under the *CCfD* regime, the carbon price is socially optimal, but too few firms invest in the emission-free technology. *Commitment* falls equally short of the socially optimal investment level. In addition, it achieves a lower consumer surplus due to a sub-optimal carbon price. Hence we derive the ranking:

$$E[\mathcal{W}^{Opt}_{\sigma_D}] = E[\mathcal{W}^{Flex}_{\sigma_D}] \geq E[\mathcal{W}^{CCfD}_{\sigma_D}] \geq E[\mathcal{W}^{Com}_{\sigma_D}] \tag{5.27}$$

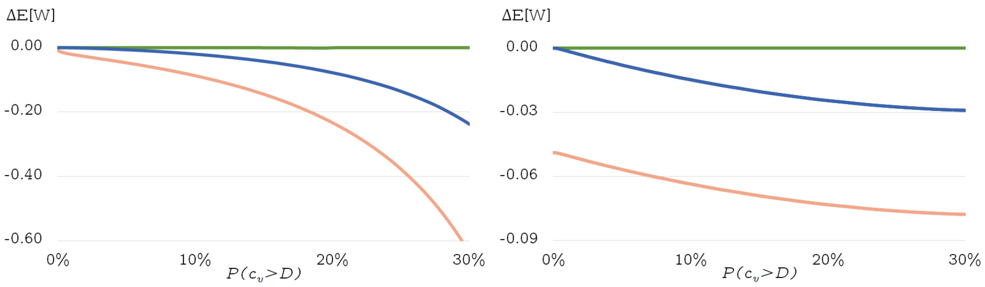
First, we find that *Regulatory Flexibility* reaches the social optimum. The firms face a carbon price equal to the marginal environmental damage and, thus, their production decision is socially optimal. Concurrently, as the firms are risk neutral, volatile profits do not impede investments.

Second, welfare falls short of the social optimum if the regulator offers a CCfD. Firms' production decision is independent of the actual carbon damage, such that emission-free production is safeguarded even if it is ex-post socially not optimal. We find that with an increasing probability of ex-post welfare-reducing production, welfare increasingly falls short of the social optimum. The probability of situations in which emission-free production is socially not optimal depends both on the variance (σ_D) and the expected value (μ_D) of the environmental damage. However, the impact of these two factors differs. As the expected value of environmental damage decreases, the welfare-deterring effect of the *CCfD* regime is partially mitigated as the socially optimal emission-free production capacity decreases, too. Figure 5.7 illustrates these findings for a numerical example.[67] We provide an analytical proof showing the welfare superiority of *Regulatory Flexibility* compared to the *CCfD* regime in D.4. Figure 5.7i presents welfare changes induced by an increase of the variance of the damage, σ_D, and Figure 5.7ii welfare changes induced by an increase of the mean of the environmental damage, μ_D.

Third, confirming the results of Habermacher and Lehmann (2020), we find that *Com* likewise falls short of the social optimum. Moreover, *Com* performs worse than offering a CCfD. In addition to the welfare-reducing production, committing to a carbon price early on does not only affect producers but also consumers. Suppose the probability of socially not optimal production increases due

[67] These parameter values are illustrative and do not correspond to empirical estimates. Both, Figure 5.7i and Figure 5.7ii, share the parameters regrading the demand $Q(p) = 5 - 0.4p$ and the costs related to the emission-free technology $c_v = 2$ and $c_i = 1$.

to an increase of the damage variance, both the production and the consumption decisions are increasingly distorted. As a result, the welfare deterring effect in comparison to the *CCfD* regime increases. In turn, if the probability of socially not optimal production increases due to a reduced difference between μ_D and c_v, the shortfall in welfare is unaffected. We depict these results in Figure 5.7.



(i) Change in $P(c_v > D)$ due to an increase in σ_D

(ii) Change in $P(c_v > D)$ due to a decrease in μ_D

Figure specific parameters in (i): $D \sim N(\mu_D = 2.75, \sigma_D^2 \in [0, 1.5]$ and (ii): $D \sim N(\mu_D \in [2.25, 3.5]), \sigma_D^2 \in (0, 1.5])$.

Figure 5.7.: Difference in welfare compared to social optimum in the presence of damage risk and potentially welfare-reducing production.

5.4.3. Numerical application with risk aversion

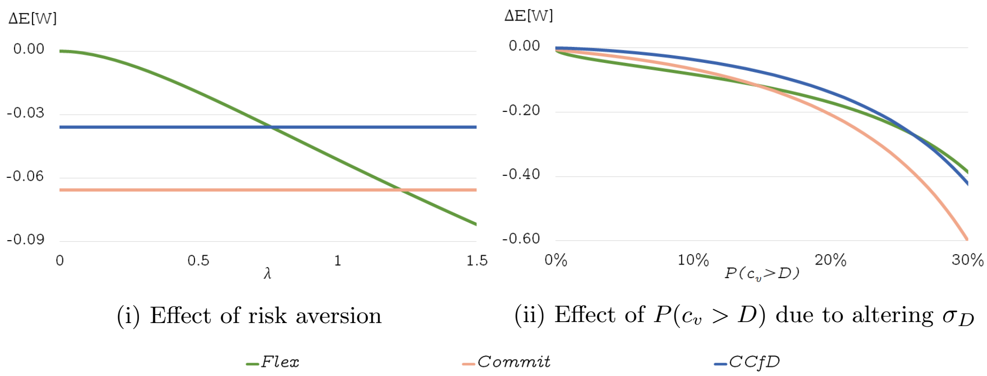
We complement our analytical results with a numerical application. The primary intention of this numerical exercise is to show how firms' risk aversion alters the effect of potentially welfare-reducing production in case of damage risk. Like in section 5.3, we assume the firms to have a utility which is exponential in profits (i.e., $EU[\pi(\chi)] = E[1 - e^{\pi(\chi)}]$. We find that the introduction of risk aversion reduces the superiority of *Regulatory Flexibility* and generates a trade-off for the regulator between incentivizing investments and triggering socially optimal production. Note that these parameter values are illustrative and do not correspond to empirical estimates.[68] For the analysis, we vary two parameters in our model: firms' risk aversion and the distribution of the environmental damage. The latter results in different probabilities of socially not optimal production, i.e., how likely it is that variable costs of abatement are ex-post higher than the marginal environmental damage.

To illustrate the effects of these two variations, we calculate the expected welfare levels of the carbon pricing regimes and compare them to the social optimum. Figure 5.8 depicts the results. In Figure 5.8i, we analyze the impact of firms' risk

[68] Figure 5.8i and Figure 5.8ii share the parameters regarding the demand $Q(p) = 5 - 0.1$ and the costs related to the emission-free technology $c_v = 4$ and $c_i = 1$.

aversion. Extending our analytical results for the case without risk aversion, *Commitment* and *CCfD* do not result in the social optimum, whereby the *CCfD* regime is superior to *Com*, as it sets the socially optimal carbon price. Firms' risk aversion does not impact the welfare levels as both regimes remove risk for the firms. Also reflecting the results of section 5.4.2, the *Flex* regime results in the social optimum if firms are risk neutral. However, as the risk aversion increases, fewer firms invest in the emission-free technology, whereby the expected welfare of this policy regime decreases. If this investment hampering effect of risk aversion becomes sufficiently large, the *Flex* regime becomes welfare inferior to *Com* and *CCfD*. Hence, there is a trade-off between the effects identified in section 5.3.2 and 5.4.2.

Figure 5.8ii shows a similar effect when varying the probability of socially not optimal production by altering the variance of the marginal damage as $P(C_v > D)$ increases in σ_D.[69] With increasing volatility, *Flex* becomes less efficient as firms' risk aversion increasingly impedes investments. Offering a CCfD and committing to a carbon price, in contrast, become less efficient due to the increasing probability of welfare-reducing production arising from increased volatility. The level of risk aversion does not impact this effect. Under *Com*, the ex-post socially not optimal carbon price also applies for consumers, such that welfare is lower than in the *CCfD* regime. With an increasing probability of socially not optimal production, the welfare-deterring effect of *CCfD* and *Com* becomes more pronounced compared to the *Flex* regime. Hence, with an increasing probability of welfare-reducing production, the *Flex* regime becomes welfare superior to *Com* and *CCfD*.[70]



(i) Effect of risk aversion

(ii) Effect of $P(c_v > D)$ due to altering σ_D

Figure specific parameters in (a): $\lambda \in [0, 1.5]$, $D \sim N(\mu_D = 2.75, \sigma_D^2 = 0.7803)$ such that $P(c_v > D) = 10\%$ and (b): $\lambda = 1.5$, $D \sim N(\mu_D = 5, \sigma_D^2 \in (0, 2])$.

Figure 5.8.: Difference in welfare compared to social optimum in the presence of damage risk, potentially welfare-reducing production and risk aversion.

[69] In this illustrative example, all carbon pricing regimes achieve the social optimum at $P(C_v > D) = 0$. This is only the case because $\sigma_D = 0$ holds as well.

[70] When changes in the probability of socially not optimal production stem from decreasing the difference between μ_D and c_v, similar effects occur (see D.6).

Both numerical simulations show that the superiority of the respective carbon price regime is ambiguous and depends on specific parameters. However, if the regulator had to choose between offering a CCfD and committing to a carbon price early on, i.e., before the risk resolves, it is always beneficial to provide a CCfD.

5.5. Discussion

In the previous sections, we showed under which circumstances offering a CCfD can be a valuable policy measure. CCfDs could increase welfare compared to a flexible carbon price if the regulator expects that, first, firms will significantly under-invest in an abatement technology in the presence of risk and, second, the probability of welfare-reducing emission-free production is low. In other words, a CCfD is only beneficial if the benefit from the additional abatement that it incentivizes outweighs the risk that it supports a technology that is socially not optimal.

There are several considerations beyond our model setup determining whether a CCfD is an efficient policy instrument. First, it matters who can enter a CCfD. While policy constraints may imply that a regulator should offer CCfDs only to limited sectors, for instance, heavy industry, our research indicates that they may be helpful in a broader range of settings in which agents make insufficient investments for decarbonization because of the presence of risk. Second, the variance of the variable at risk may increase with a longer duration of the CCfD. Hence, the probability of supporting an ex-post welfare-reducing technology may increase with the duration. Third, the process of how the regulator grants a CCfD determines its impact on welfare. Suppose the CCfD only addresses the risk regarding the valuation of damage. In that case, the strike price should equal the regulator's damage expectation, and she can offer the CCfD to any interested party. If, however, the regulator aims to address private information, for instance, on the expected variable costs or firms' risk aversion, an auction process may be preferable to minimize costs for the regulator. Likewise, this holds if the CCfD involves an additional subsidy.

In addition to the carbon price risk, the regulator may introduce an instrument, similar to a CCfD, that assumes risks on the firms' variable costs. For instance, the proposal of the German funding guidelines for large-scale decarbonization investments in the industrial sector includes such an extended risk assumption by the government (BMU, 2021). The extended risk-bearing could reduce complementary investment subsidies from the regulator to risk-averse firms, as shown by Richstein et al. (2021).[71] However, the regulator would safeguard firms in situations with ex-post socially not optimal production, i.e., unexpectedly high variable costs which exceed marginal damage. Thereby, the probability of financ-

[71] In our model, e.g., in section 5.3.3, such a scheme would lower the average strike price to the expected damage and reduce the average spending of the regulator.

ing an ex-post socially not optimal technology would increase, decreasing welfare. This measure would need a reasonable justification, for instance, a significant level of firms' risk aversion or a sufficiently low probability that the low-carbon technology is socially not optimal.

Our research relies on several assumptions that, if relaxed, might dampen the identified effects and potentially change the policy rankings. Noteworthy, we assume the absence of shadow cost of public funding. Because taxation has distortionary effects, public expenses might come at a cost (e.g. Ballard and Fullerton, 1992, for a review). Including shadow costs of public funds into our model might yield two effects. First, the carbon price would optimally be higher than the marginal environmental damage. The regulator would value one unit of revenue from the carbon price at more than one unit of consumer surplus because it allows other distortionary taxes to be reduced (see, e.g., Helm et al., 2003, for a discussion of this *weak form* of a double-dividend). Second, offering a CCfD would be more costly, and the regulator might require a premium for providing the contract and safeguarding the investments. If this is the case, the benefits of offering a CCfD would partially diminish. We expect a trade-off between the benefit of increased investments and the costs of additional public funds when comparing a *CCfD* regime with *Regulatory Flexibility* and *Commitment*.

Similarly, the regulator may also be risk averse. In this case, we can see the three carbon pricing regimes from the angle of who bears the risk (see Hepburn, 2006, for a discussion of risk-sharing between the government and the private sector). While the risk remains with the firms under *Regulatory Flexibility*, the regulator assumes the risk under *Commitment* and *CCfD*. Suppose a risk-averse regulator bears the risk in the presence of an unknown valuation of environmental damage. To reduce the negative welfare effects in case of great environmental damage, she would set a higher strike price when offering a CCfD or increase the carbon price under *Commitment*. In contrast, with variable cost risk, she prefers incentivizing a lower level of investment to reduce her risk. This aspect may change the policy ranking of the three carbon pricing regimes.

We analyze a setting where carbon prices determined by the marginal environmental damage result in a demand that exceeds the optimal emission-free production capacity. However, we could think of settings, in which demand can be covered entirely by the emission-free production. In these settings, the conventional technology would not produce. Hence, the marginal utility of consumption, given the production capacity of the emission-free technology, would determine the product price. In consequence, if firms would assume the product price to be set by the conventional technology, some of the firms using the emission-free technology would incur a loss. Instead, firms would anticipate a product price below the carbon price and reduce their investment. The marginal firm would avoid a loss by balancing its investment costs with the contribution margin, which is reduced to lower prices. If the firm cannot pass through its investment costs, it would not invest in the first place. The model would not have an equilibrium.

Broadly speaking, if the regulator aims to fully replace the conventional technology, offering a CCfD is not an adequate policy. The instrument implicitly assumes that the profit of the emission-free technology is linked to the carbon price. This is only the case if the conventional technology sets the market price because the emission-free technology is not subject to the carbon price. For the same reason, CCfDs can only support a technology switch in an existing product market but not the market ramp up for a new product.

Our model results focus on the effects of each type of risk separately. In reality, stakeholders likely face damage and cost risk simultaneously. If the two risks are uncorrelated, their effects are additive. Variable cost risk can lead to an investment that is too low. Damage risk can affect both investment and consumption. Hence, the welfare ranking in equation 5.10 holds and the superiority of *Commitment* or *Regulatory Flexibility* depends on the concrete circumstances. If risks are positively correlated, high environmental damage indicates high variable costs and vice versa. In this case, the emission-free production is likely to be ex-post socially optimal as $\mu_{C_V} > \mu_D$ holds. Results are then similar to the setting in section 5.3. If risks are negatively correlated, high environmental damage indicates low variable costs and vice versa. In the case of high damage and low variable costs, emission-free production is socially optimal. In the case of low damage and high variable costs, in turn, the emission-free production is likely to be welfare reducing. Hence, if risks are negatively correlated, the situation is similar to the setting in section 5.4.

The last simplification of our model we like to stress is the assumption of constant marginal environmental damage. We do not expect our main findings regarding the ranking of the carbon pricing regimes to change if we alleviate this assumption. If the marginal environmental damage was non-constant, the regulator would still choose the Pigouvian tax level after the firms have invested. In contrast to our assumption, the tax level would depend on the number of firms using the emission-free technology, i.e., total emissions. If markets are competitive, the impact of an individual firm on total emissions is negligible, and firms' investment decisions would not change compared to our model.

5.6. Conclusion

The decarbonization of the industry sector requires large-scale irreversible investments. However, the profitability of such investments is subject to risk, as both, the underlying revenue and the associated costs of switching to an emission-free production process, are unknown and cannot be sufficiently hedged. The European Commission's Hydrogen Strategy and the *Fit for 55* package propose Carbon Contracts for Differences (CCfDs) to support firms facing large-scale investment decisions. Such contracts effectively form a hedging instrument to reduce the firms' risks.

With this research, we contribute to the understanding of how regulators should design this instrument and under which circumstances it is beneficial to offer a CCfD. We analyze the effects of a CCfD in the presence of risks stemming from environmental damage and variable costs on the decisions of a regulator and risk-averse firms facing an irreversible investment decision. Applying an analytical model, we compare three carbon price regimes against the social optimum: *Regulatory Flexibility*, *Commitment*, and offering a *CCfD*.

We conclude that a CCfD can be a welfare-enhancing policy instrument, as it encourages investments when firms' risk aversion would otherwise impede them. Additionally, offering a CCfD is always better than committing early to a carbon price as CCfDs incentivize investments in the same way while keeping the possibility to set the carbon price flexibly if new information,e.g., on the environmental damage, is available. However, if it is likely that the production of the emission-free technology turns out to be socially not optimal, CCfDs have the disadvantage that the regulator is locked in her decision, and she may distort the market clearing. In these situations, *Regulatory Flexibility* can be welfare superior to offering a CCfD. The comparison of *Regulatory Flexibility* and *Commitment* depends on the type of risk involved. With damage risk, *Regulatory Flexibility* is superior to *Commitment* if the level of risk aversion is low and the elasticity of demand is high. With variable cost risk, in contrast, *Regulatory Flexibility* performs worse than *Commitment.* While the regulator can only set the carbon price after the firm's investment under *Regulatory Flexibility*, she can balance additional investment incentives and the consumption level under *Commitment.*

This research focuses on the effects of CCfDs, aiming at mitigating the impact of risk regarding investments in emission-free technologies. Further research analyzing CCfDs with more complex features and the interactions between CCfDs and other policy instruments may broaden our understanding of this instrument. To begin with, regulators may combine a CCfD with a subsidy payment to firms. This combination may be justified if the future carbon price is too low to incentivize sufficient emission-free investments, e.g., in the presence of learning effects or other positive externalities. Research could focus on whether combining a CCfD and a subsidy has advantages over offering both instruments separately. Additionally, proposals for the use of CCfDs focus on sectors competing in international markets. Our model assumes complete cost pass-through of the carbon price and, hence, increased revenues for firms investing in abatement. If not all firms on an international market face a (similar) carbon price, this may not hold. It remains open how the design of CCfDs would need to change in such settings to ensure investments' profitability. Future analyzes could consider the possibility of introducing carbon border adjustment mechanisms, such that producers from countries without a carbon price at the domestic level cannot offer the goods at a lower price. The question how other hedging instruments offered by private actors compare to CCfDs is also worth analyzing in more detail. Moreover, future research could assess the role of shadow costs of public funds by extending our model in this regard. As pointed out in section 5.5, we assume payments under a CCfD to be welfare-neutral. Considering shadow costs of public funds may worsen the welfare ranking of CCfDs compared to pure carbon pricing regimes.

A. Supplementary Material for Chapter 2

A.1. Exogenous cost reduction in period two

Analogously to the effect of an increase of learning by doing, analyzed in section 2.2.2, we can derive the impact of an *exogenous* cost reduction in period two on the optimal distribution of abatement between both periods. Let us for this purpose adjust the analytical model from section 2.2.2 such that period-two abatement costs $C(A)$ depend on a via the intertemporal cap but not on any form of endogenous learning. Equation 2.9 that sets the cap still holds. We can rewrite the equilibrium condition from equation 2.12 to:

$$c_a(a) = \frac{C_A(A(a))}{1+r} \tag{A.1}$$

with the equilibrium function analogously to equation 2.13:

$$f(a) := c_a(a) - \frac{C_A(A(a))}{1+r} = 0. \tag{A.2}$$

We can derive the effect of an exogenous cost decrease on period-one abatement with the help of the total differential. For this, we first set up the individual derivatives:

$$\begin{aligned} f_a &= c_{aa}(a) + \frac{C_{AA}(A(a))}{1+r} \\ f_{C_A} &= -\frac{1}{1+r} \end{aligned} \tag{A.3}$$

The total differential yields

$$\begin{aligned} f_a da^* + f_{C_A} dC_A &= 0 \\ \frac{da^*}{dC_A} &= -\frac{f_{C_A}}{f_a} \\ &= \frac{1}{(1+r)c_{aa} + C_{AA}} \\ &> 0 \end{aligned} \tag{A.4}$$

As $c_{aa}, C_{AA} > 0$, the total differential is positive. An exogenous decrease of period-two marginal abatement costs leads to a decrease in period-one abatement. In other words, an expected future cost decrease leads to a postponement of abatement efforts. The expectation of an exogenous cost reduction features the *Hotelling effect* but not the *learning effect*.

B. Supplementary Material for Chapter 3

B.1. Optimization of the Firm, Lagrange Function and KKT Conditions

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:

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

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:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial x(t)} &= \frac{1}{(1+r)^t}p(t) - \lambda(t) &&= 0 \quad \forall\, t = 1, 2, \ldots, T && \text{(B.3)}\\
\frac{\partial \mathcal{L}}{\partial e(t)} &= (-1)\frac{1}{(1+r)^t}c(u - e(t)) + \lambda(t) &&= 0 \quad \forall\, t = 1, 2, \ldots, T && \text{(B.4)}\\
\frac{\partial \mathcal{L}}{\partial b(t)} &= \lambda(t) - \lambda(t+1) - \mu_b(t) &&= 0 \quad \forall\, t = 1, 2, \ldots, T. && \text{(B.5)}
\end{aligned}$$

Primal feasibility:

$$\begin{aligned}
b(t) - b(t-1) - x(t) + e(t) &= 0 \quad \forall\, t = 1, 2, \ldots, T && \text{(B.6)}\\
x(t),\ \ e(t) &\gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. && \text{(B.7)}
\end{aligned}$$

Dual feasibility and complementarity:

$$\begin{aligned}
0 \leq b(t) \perp \mu_b(t) &\geq 0 \quad \forall\, t = 1, 2, \ldots, T && \text{(B.8)}\\
\lambda(t) &\gtrless 0 \quad \forall\, t = 1, 2, \ldots, T. && \text{(B.9)}
\end{aligned}$$

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

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

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.

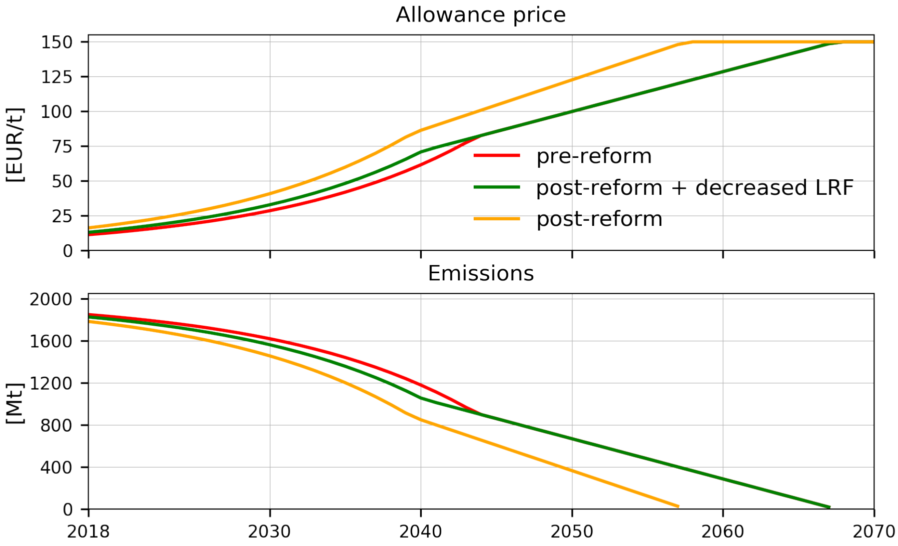


Figure B.1.: Effect of the CM

C. Supplementary Material for Chapter 4

C.1. Sensitivity analysis of the cancellation threshold

Figure C.1 shows that the finding, that a CM based on fixed threshold of 400 million allowances does not significantly change the cancelled volume compared to the regulation in place, also holds for other threshold levels. As the *Fit for 55* proposal can only enter into force by 2024, the new rule would not be valid for the first cancellation in 2023. For cancellation thresholds lower than 400 million allowances, the cancellation volume in 2023 and 2024 increases slightly more than proportionally to the threshold increase as more cancellation induces a feedback with higher prices and even more abatement, a higher TNAC and more MSR intake and cancellation. However, a tighter threshold does not induce cancellation in 2025 as long as there is no additional MSR intake. In this way, even an extreme threshold of zero, i.e., all MSR allowances are automatically rendered invalid after 2023, leads to an increase of the overall cancellation volume of only 475 million allowances or 18.9% compared to the thresholds in the *Fit for 55* scenario. While the cancellation volume analogously decreases for higher thresholds, it remains unchanged for thresholds above 700 million allowances as at this threshold there is no cancellation triggered in 2024 when the proposed regulation could enter into force.

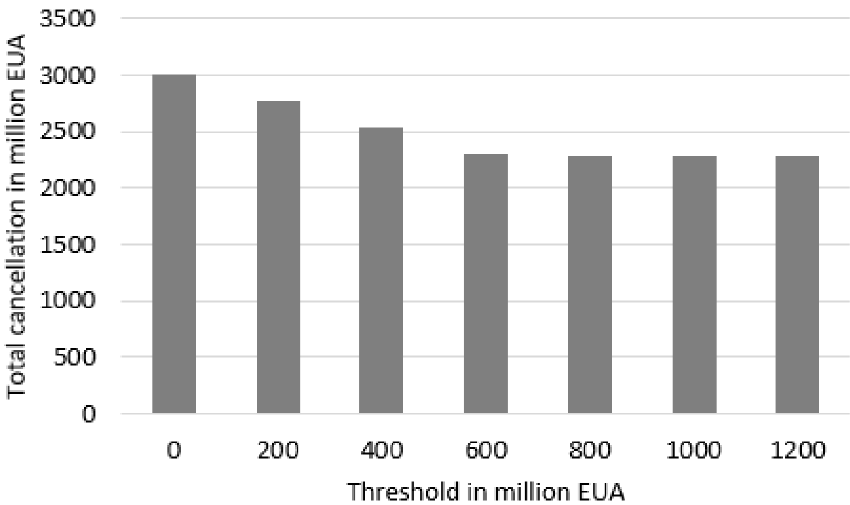


Figure C.1.: Cancellation volume under different cancellation thresholds

C.2. Further scenario comparison

Analogously to the decomposition of cancellation volumes presented in Figure 4.10, Figure C.2 presents the change of total emission levels in the EU ETS (over the entire model horizon) induced by the three reform elements. The impact of the MSR and CM adjustments on total emission levels is negligible.

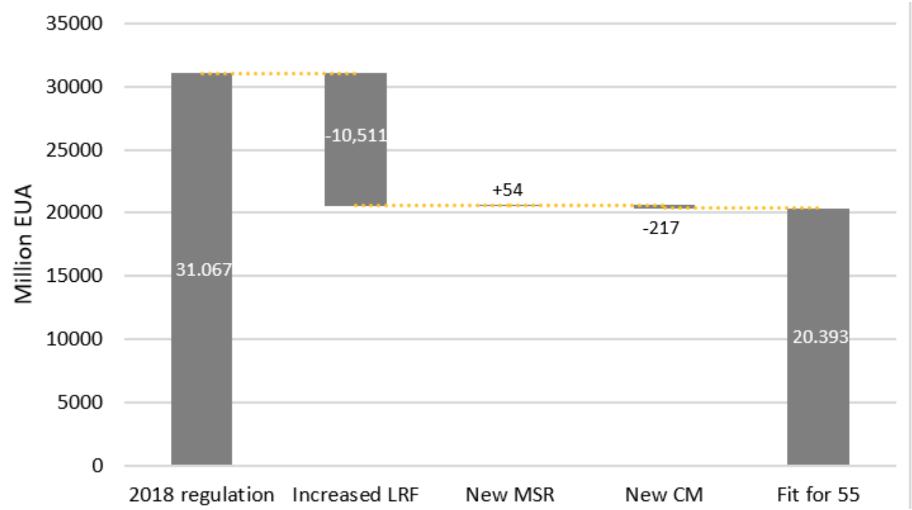


Figure C.2.: Decomposition of changes in total emissions into the individual reform elements

Similarly, change in the 2021 abatement level is mainly induced by the increased LRF, while MSR and CM adjustments play a minor role, as figure C.3 shows.

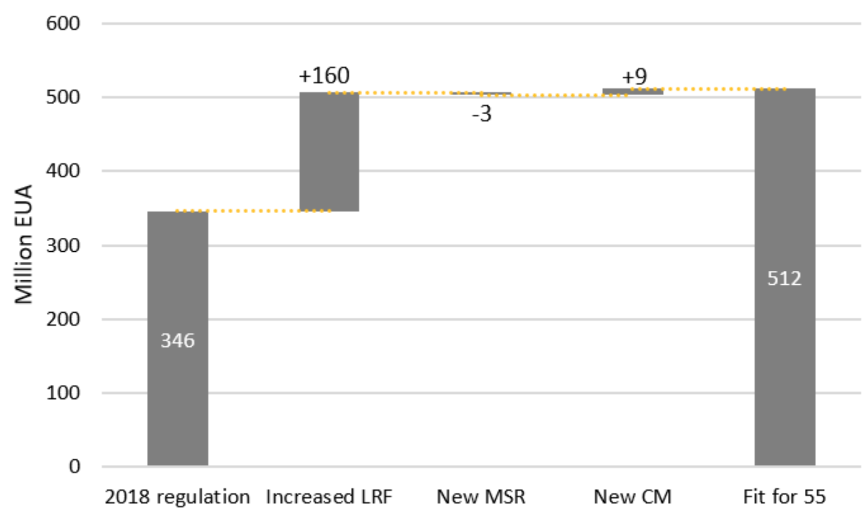


Figure C.3.: Decomposition of changes in 2021 abatement levels into the individual reform elements

D. Supplementary Material for Chapter 5

D.1. Proof of Proposition 5.2.1

For the proof of Proposition 5.2.1, we compare the socially optimal outcome to the three carbon pricing regimes. In the following, we derive the outcomes of these regimes.

Regulatory flexibility

In a setting with *Regulatory flexibility*, the regulator sets the carbon price after the firms have invested in the emission-free technology. The regulator faces the optimisation problem:

$$\max_p \mathcal{W} = \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \tag{D.1}$$

We derive the optimal solution by deriving the first-order conditions:

$$\frac{\partial \mathcal{W}}{\partial p} = -Q(p) + Q(p) + Q'(p)(p-d) = 0 \longrightarrow p^{Flex} = d \tag{D.2}$$

As in the social optimum, the carbon price equals the damage of one additional unit of the good. In t_3, the investments are already set, and, hence, the social planner and the regulator face identical problems. The carbon price does not influence the emission-free production capacity but only determines the optimal level of consumption and, in consequence, pollution.

In t_2, the firms choose to invest in the emission-free technology, as long as the associated profits are positive. Firms anticipate the carbon price that arises in the subsequent stage. The profit of the marginal firm investing in the emission-free technology is zero and, hence, the emission-free production capacity is defined by

$$\begin{aligned} \pi(\overline{\chi}) &= p^{Flex} - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Flex} &= \frac{p^{Flex} - c_v}{c_i} \end{aligned} \tag{D.3}$$

The optimal emission-free production capacity is at the socially optimal level, as the carbon price set in t_3 equals the marginal damage ($p^{Flex} = d$), i.e. $\overline{\chi}^{Flex} = {}^{d-c_v}/_{c_i}$.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms choose to invest in the emission-free technology if the associated profits are positive, such that the marginal firm investing is defined by:

$$\begin{aligned}\pi(\overline{\chi}) &= p - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Com} &= \frac{p - c_v}{c_i}\end{aligned} \tag{D.4}$$

In t_1, the regulator chooses the carbon price that maximises the social welfare function while anticipating the reaction function of firms to the announced price.

$$\begin{aligned}\max_p \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p)} (d - c_v - c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p-d) + \overline{\chi}'(p)(d - c_v - c_i\overline{\chi}) = 0\end{aligned} \tag{D.5}$$

Inserting the optimal investment level $\overline{\chi}^{Com}$ from (D.4), the expression yields:

$$Q'(p)(p-d) = \overline{\chi}'(p)(p-d) \longrightarrow \quad p^{Com} = d \tag{D.6}$$

As under *Regulatory flexibility*, the solution yields the social optimum. In the absence of risk, there is no difference for the regulator in setting the carbon price in t_1 or t_3.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms invested in the emission-free technology. The solution yields the same result as under *Regulatory flexibility*, as the regulator can only control the size of the market at this stage.

$$\begin{aligned}&\max_p \mathcal{W} = \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz \\ &\longrightarrow \ p^{CCfD} = d\end{aligned} \tag{D.7}$$

In t_2, the firms choose to invest in the emission-free technology according to their profit function, which depends on the strike price of the CCfD. The carbon price is irrelevant to the firms.

$$\begin{aligned}\pi(\overline{\chi}) &= p_s - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{p_s - c_v}{c_i}\end{aligned} \tag{D.8}$$

The result is the socially optimal emission-free production capacity that balances the marginal costs and the benefit of abatement, i.e., savings from reduced payment of the strike price. In t_1, the regulator chooses the strike price that she offers to the firms. She faces the following optimisation problem:

$$\begin{aligned}\max_{p_s} \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p_s} &= [d - c_v - c_i\overline{\chi}(p_s)]\overline{\chi}'(p_s) = 0\end{aligned} \tag{D.9}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (D.8), the expression yields $p_s^{CCfD} = d$. Hence, the strike price equals marginal damage, and the strike price and carbon price have the same level in the absence of risk. Firms and consumers receive the same signal regarding the benefit from investments or the damage from consumption, respectively. Both prices are at the socially optimal level.

Welfare ranking

As all three carbon pricing regimes result in the socially optimal carbon price and the socially optimal emission-free production capacity, it is straightforward that the respective welfare is equal to the social optimum.

D.2. Proof of Proposition 5.3.1

For the proof of Proposition 5.3.1, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

Social optimum

In the social optimum, the social planner sets the carbon price p in t_3 after the actual environmental damage revealed. She optimises:

$$\max_{p} \mathcal{W} = \int_p^\infty Q(z)dz + (p-\hat{d})Q(p) + \int_0^{\overline{\chi}} (\hat{d} - c_v - c_i z)dz \tag{D.10}$$

Given the first-order conditions, the optimal solution is equal to:

$$\frac{\partial \mathcal{W}}{\partial p} = -Q(p) + Q(p) + Q'(p)(p-\hat{d}) = 0 \longrightarrow p^{Opt} = \hat{d} \tag{D.11}$$

The investments are due before the actual damage reveals. Hence, the social planner must choose the emission-free production capacity in the presence of risk.

The social planner optimises the expected welfare with respect to the emission-free production capacity $\overline{\chi}$.

$$\max_{\overline{\chi}} E[\mathcal{W}] = E\left[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}} (d - c_v - c_i z)dz\right] \tag{D.12}$$

Given the expected damage, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = E[d] - c_v - c_i\overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{E[d] - c_v}{c_i} = \frac{\mu_D - c_v}{c_i} \tag{D.13}$$

Regulatory flexibility

Under *Regulatory flexibility*, similar to the assumption of a social planner, the regulator sets the carbon price after the actual damage revealed. As shown in D.1, in this case, the regulator and the social planner have the same objective function. Hence, in *Flex*, the regulator optimises (D.10), which yields $p^{Flex} = \hat{d}$.

In t_2, the firms choose to invest in the emission-free technology, as long as the associated profits are positive. They anticipate the subsequent carbon price:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= E[p^{Flex}] - c_v - c_i\overline{\chi} - \lambda\sigma_{p^{Flex}} = 0 \\ \longrightarrow \overline{\chi}^{Flex} &= \frac{p^{Flex} - c_v - \lambda\sigma_{p^{Flex}}}{c_i} = \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} \end{aligned} \tag{D.14}$$

where the last step stems from replacing the statistical moments of the carbon price in *Flex* with the ones of the environmental damage, i.e., $E[p^{Flex}] = \mu_D$ and $\sigma_{p^{Flex}} = \sigma_D$. The emission-free production capacity decreases with the volatility of the environmental damage and firms' risk aversion, as $\frac{\partial \overline{\chi}^{Flex}}{\partial \lambda} = -\frac{\sigma_D}{c_i}$ and $\frac{\partial \overline{\chi}^{Flex}}{\partial \sigma_D} = -\frac{\lambda}{c_i}$ are both smaller than zero.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms make their investment decision given the announced carbon price level. In this setting, all parameters are known, such that firms face no risk:

$$\begin{aligned} \pi(\overline{\chi}) &= p - c_v - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Com} &= \frac{p - c_v}{c_i} \end{aligned} \tag{D.15}$$

In t_1, the regulator sets the carbon price maximising expected welfare and accounting for the firms' reaction function to the announced price:

$$\max_p E[\mathcal{W}] = E\left[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p)} (d - c_v - c_i z)dz\right]$$

$$\frac{\partial E[\mathcal{W}]}{\partial p} = -Q(p) + Q(p) + Q'(p)(p-\mu_D) + \overline{\chi}'(p)(\mu_D - c_v - c_i\overline{\chi}) = 0 \tag{D.16}$$

Inserting the resulting emission-free production capacity $\overline{\chi}^{Com}$ from (D.15), the expression yields:

$$Q'(p)(p-\mu_D) = \overline{\chi}'(p)(p-\mu_D) \longrightarrow \quad p^{Com} = \mu_D \tag{D.17}$$

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (D.10), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = \hat{d}$.

In t_2, the firms choose to invest accounting for the strike price of the CCfD. The carbon price is irrelevant to firms. Hence, the maximisation problem is identical to (D.8), and the solution is equal to:

$$\overline{\chi}^{CCfD} = \frac{p_s - c_v}{c_i} \tag{D.18}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\begin{aligned}\max_{p_s} E[\mathcal{W}] &= E\left[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz\right] \\ \frac{\partial E[\mathcal{W}]}{\partial p_s} &= [\mu_D - c_v - c_i\overline{\chi}(p_s)] = 0\end{aligned} \tag{D.19}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (D.18), the first-order condition yields $p_s^{CCfD} = \mu_D$. Hence, the strike price equals the expected marginal damage. Inserting p_s^{CCfD} into (D.18) shows that the investment level is socially optimal and equals the solution under *Commitment*.

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and in the *CCfD* regime. Thus, welfare in the *CCfD* regime and in the social optimum is identical, i.e., $E[\mathcal{W}^{Opt}_{\sigma_D}] = E[\mathcal{W}^{CCfD}_{\sigma_D}]$.

The emission-free production capacity under *Regulatory flexibility* is lower than the under the *CCfD* regime, as:

$$\overline{\chi}^{CCfD} - \overline{\chi}^{Flex} = \frac{\mu_D - c_v}{c_i} - \frac{\mu_D - c_v - \lambda\sigma_D}{c_i} = \frac{\lambda\sigma_D}{c_i} \geq 0 \tag{D.20}$$

Expected welfare increases with the number of firms investing in the emission-free technology, as long as $\overline{\chi} \leq \overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$, since $\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = \mu_D - c_v - c_i\overline{\chi}$ which is a positive number for all $\overline{\chi} < \frac{\mu_D - c_v}{c_i}$. Hence, welfare under regulatory flexibility is lower than socially optimal, i.e., $E[\mathcal{W}_{\sigma_D}^{CCfD}] \geq E[\mathcal{W}_{\sigma_D}^{Flex}]$.

The difference in welfare between the policy regimes of *Commitment* and *CCfD* stems from the difference in consumer surplus, as the respective emission-free production capacity are identical. Since the consumer surplus is a convex function, the welfare difference is positive:[72]

$$E[\mathcal{W}_{\sigma_D}^{CCfD}] - E[\mathcal{W}_{\sigma_D}^{Com}] = E[\int_D^\infty Q(z)dz] - \int_{\mu_D}^\infty Q(z)dz \geq 0 \tag{D.21}$$

Hence, it holds that $E[\mathcal{W}_{\sigma_D}^{CCfD}] \geq E[\mathcal{W}_{\sigma_D}^{Com}]$.

Whether the difference in expected welfare between *Flex* and *Com* is positive or not, is ambiguous. The difference is equal to

$$\begin{aligned} E[\mathcal{W}_{\sigma_D}^{Flex}] - E[\mathcal{W}_{\sigma_D}^{Com}] = & \underbrace{E[\int_D^\infty Q(z)dz] - \int_{\mu_D}^\infty Q(z)dz}_{\geq 0} \\ & \underbrace{+(\mu_D - c_v)(\overline{\chi}^{Flex} - \overline{\chi}^{Com}) - \int_{\overline{\chi}^{Com}}^{\overline{\chi}^{Flex}} (c_i z)dz}_{\leq 0}, \end{aligned} \tag{D.22}$$

where the first part, i.e., difference in consumer surplus, is positive and the second part, i.e., the difference in abatement benefit, is negative.

D.3. Proof of Proposition 5.3.2

For the proof of Proposition 5.3.2, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

[72] This relation is also known, as Jensen gap stemming from Jensen's inequality.

Social optimum

In the social optimum, the social planner sets in t_3 the carbon price p after the actual level of variable costs revealed. She optimises:

$$\begin{aligned}\max_p \mathcal{W} &= \int_p^\infty Q(z)dz + (p-d)Q(p)\int_0^{\overline{\chi}}(d-\hat{c_v}-c_i z)dz \\ \frac{\partial \mathcal{W}}{\partial p} &= -Q(p) + Q(p) + Q'(p)(p-d) = 0\end{aligned} \tag{D.23}$$

Given the first-order condition, the optimal solution is equal to $p^{Opt} = d$.

The investments are due before the level of variable costs reveals. Hence, the social planner must set the emission-free production capacity in the presence of risk. The social planner optimises the expected welfare with respect to the emission-free production capacity $\overline{\chi}$, as depicted in (D.12). Given the expected variable costs, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = d - E[c_v]c_i - \overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{d-\mu_{C_v}}{c_i} \tag{D.24}$$

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price in t_3. Again, the regulator and the social planner have the same objective function. Hence, under *Regulatory flexibility*, the regulator optimises (D.23), which yields $p^{Flex} = d$.

In t_2, the firms take their investment decision, anticipating the risk in variable costs that arises in the subsequent stage:

$$\begin{aligned}EU(\pi(\overline{\chi})) &= p^{Flex} - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ \longrightarrow \overline{\chi}^{Flex} &= \frac{p^{Flex}-\mu_{C_v}-\lambda\sigma_{C_v}}{c_i} = \frac{d-\mu_{C_v}-\lambda\sigma_{C_v}}{c_i}\end{aligned} \tag{D.25}$$

where the last step stems from replacing the optimal carbon price in *Flex.* The emission-free production capacity decreases with the volatility of the variable costs and the firms' risk aversion, as $\frac{\partial\overline{\chi}^{Flex}}{\partial\lambda} = -\frac{\sigma_{C_v}}{c_i}$ and $\frac{\partial\overline{\chi}^{Flex}}{\partial\sigma_{C_v}} = -\frac{\lambda}{c_i}$, which both are smaller than zero.

Commitment

When the regulator commits to a carbon price, she faces no decision in t_3. In t_2, the firms choose to invest in the emission-free technology given the announced carbon price level. In this setting, the firms still face a risk, stemming from the variable costs. The firms invest if their expected utility is greater than zero.

Hence, the marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= p^{Com} - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ \longrightarrow \overline{\chi}^{Com} &= \frac{p^{Com} - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \end{aligned} \tag{D.26}$$

In t_1, the regulator sets the carbon price maximising expected welfare and accounting for the reaction function of the firms to the announced price:

$$\begin{aligned} \max_p E[\mathcal{W}] &= E\left[\int_p^\infty Q(z)dz + (p-d)Q(p)\int_0^{\overline{\chi}}(d - \hat{c_v} - c_i z)dz\right] \\ \frac{\partial E[\mathcal{W}]}{\partial p} &= Q'(p)(p-d) + \overline{\chi}'(p)(d - \mu_{C_v} - c_i\overline{\chi}(p)) = 0 \\ \longrightarrow p - d &= \frac{\overline{\chi}'(p)}{-Q'(p)}(d - \mu_{C_v} - c_i\overline{\chi}(p)) \end{aligned} \tag{D.27}$$

Rearranging the first-order condition and substituting $\epsilon(p) = -\frac{\partial Q(p)}{\partial p}\frac{p}{Q(p)}$ yields the expression in (5.14). Additionally, we define $\eta = \frac{\overline{\chi}'(p)}{-Q'(p)}$. Substituting η in (D.27) and using $\overline{\chi}(p)^{Com}$ from (D.26), yields

$$p^{Com} = d + \frac{\eta}{1+\eta}\lambda\sigma_{C_v} \tag{D.28}$$

The resulting carbon price is greater than the environmental damage d, as η is a positive number.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (D.23), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = d$.

In t_2, the firms invest in the emission-free technology accounting for the strike price of the CCfD. As in the other carbon pricing regimes, the firms face a risk in variable costs. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= p_s - E[c_v] - c_i\overline{\chi} - \lambda\sigma_{C_v} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i} \end{aligned} \tag{D.29}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\max_{p_s} E[\mathcal{W}] = E\left[\int_p^\infty Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}(p_s)} (d - c_v - c_i z)dz\right]$$
$$\frac{\partial E[\mathcal{W}]}{\partial p_s} = d - \mu_{C_v} - c_i\overline{\chi}(p_s) = 0 \quad \text{(D.30)}$$

Inserting the optimal investment level $\overline{\chi}^{CCfD}$ from (D.29), the first-order condition is equal to

$$\left(\frac{d-\mu_{C_v}}{c_i} - \frac{p_s - \mu_{C_v} - \lambda\sigma_{C_v}}{c_i}\right) = 0 \quad \text{(D.31)}$$

, which yields $p_s^{CCfD} = d + \lambda\sigma_{C_v}$. Inserting p_s^{CCfD} into (D.29) shows that the emission-free production capacity is equal to tne one under a social planner, i.e., $\overline{\chi}^{CCfD} = \frac{d-\mu_{C_v}}{c_i}$

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and in the *CCfD* regime. Thus, welfare in the *CCfD* regime and in the social optimum is identical, i.e., $E[\mathcal{W}^{Opt}_{\sigma_{C_v}}] = E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}]$.

Similar to the case of damage risk in D.2, the emission-free production capacity under *Regulatory flexibility* is lower than the under the *CCfD* regime, as:

$$\overline{\chi}^{CCfD} - \overline{\chi}^{Flex} = \frac{\lambda\sigma_{C_v}}{c_i} \geq 0 \quad \text{(D.32)}$$

Expected welfare increases in the emission-free production capacity $\overline{\chi}$, as long as $\overline{\chi} \leq \overline{\chi}^{CCfD} = \frac{d-\mu_{C_v}}{c_i}$, since $\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = d - \mu_{C_v} - c_i\overline{\chi}$. Hence, welfare in *Flex* is lower than socially optimal, i.e., $E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Flex}_{\sigma_{C_v}}]$.

To show that offering a CCfD is welfare superior to *Commitment*, we first compare the strike price with optimal carbon price in *Com*. Inserting $\overline{\chi}^{Com}$ and rearranging (D.28), yields:

$$p^{Com} - p_s = d + \frac{\eta}{1+\eta}\lambda\sigma_{C_v} - (d + \lambda\sigma_{C_v}) = \left(\frac{\eta}{1+\eta} - 1\right)\lambda\sigma_{C_v} \quad \text{(D.33)}$$

As η is a positive number, the first expression is negative and the difference is negative. Hence, we see that the optimal carbon price under commitment p^{Com} is smaller than the strike price of the CCfD. Consequently, the emission-free production capacity in *Com* is lower than when offering a CCfD, i.e., $\overline{\chi}^{CCfD} \geq \overline{\chi}^{Com}$. Similarly, it is straightforward to show that the carbon price under the *Com* regime is higher than under the *CCfD* regime. Both variables lead to lower welfare and, hence, we show that $E[\mathcal{W}^{CCfD}_{\sigma_{C_v}}] \geq E[\mathcal{W}^{Com}_{\sigma_{C_v}}]$.

To show that in this setting, *Commitment* to a carbon price is welfare superior to *Regulatory flexibility*, we can make use of the optimality of the carbon price in *Com*. The regulator sets a price above the marginal environmental damage to incentivise additional investments. She could, however, choose not to. We show the optimality by comparing:

$$\begin{aligned}
&E[\mathcal{W}^{Com}_{\sigma_{C_v}}] \\
&\quad = E\left[\int_{p^{Com}}^{\infty} Q(z)dz + (p^{Com} - d)Q(p) + d\overline{\chi}^{Com} - \frac{c_i}{2}(\overline{\chi}^{Com})^2 - c_v\overline{\chi}^{Com})\overline{Q}\right] \\
&\quad \geq E\left[\int_{p^{Flex}}^{\infty} Q(z)dz + (p^{Flex} - d)Q(p) + d\overline{\chi}^{Com} - \frac{c_i}{2}(\overline{\chi}^{Com})^2 - c_v\overline{\chi}^{Com})\overline{Q}\right] \\
&\quad \geq E\left[\int_{p^{Flex}}^{\infty} Q(z)dz + (p^{Flex} - d)Q(p) + d\overline{\chi}^{Flex} - \frac{c_i}{2}(\overline{\chi}^{Flex})^2 - c_v\overline{\chi}^{Flex})\overline{Q}\right] \\
&\quad = E[\mathcal{W}^{Flex}_{\sigma_{C_v}}],
\end{aligned} \tag{D.34}$$

where the first inequality is given by the optimality of p^{Com} and the second by the fact that $\overline{\chi}^{Flex} \leq \overline{\chi}^{Com}$ (c.f. Chiappinelli and Neuhoff, 2020).

D.4. Proof of Proposition 5.4.1

For the proof of Proposition 4, we derive the optimal solutions in the respective carbon pricing regimes and under the assumption of a social planner.

Social optimum

In t_3, the social planner sets the carbon price p after the actual environmental damage revealed, by optimising (D.10). Hence, the optimal carbon price is equal to $p^{Opt} = \hat{d}$.

In t_2, the social planner sets the emission-free production capacity under risk such that it maximises the expected welfare. She considers the cases in which production may not be optimal, i.e., $c_v > \hat{d}$.

$$\begin{aligned}
\max_{\overline{\chi}} E[\mathcal{W}] =& P\Big(\int_p^{\infty} Q(z)dz + (p-\hat{d})Q(p) + \int_0^{\overline{\chi}}(\hat{d} - c_v - c_i z)dz \mid c_v \leq p\Big) \\
&+ P\Big(\int_p^{\infty} Q(z)dz + (p-\hat{d})Q(p) - \int_0^{\overline{\chi}}(c_i z)dz \mid c_v > p\Big) \\
=& \int_p^{\infty} Q(z)dz + (p-\mu_D)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz + \int_{c_v}^{\infty} \overline{\chi}(z-c_v)f_D(z)dz
\end{aligned} \tag{D.35}$$

, where $f_D(z)$ is the density function of the environmental damage. Given the first-order condition, the optimal solution is equal to:

$$\frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} = \int_{c_v}^{\infty}(z-c_v)f_D(z)dz - c_i\overline{\chi} = 0 \longrightarrow \overline{\chi}^{Opt} = \frac{\int_{c_v}^{\infty}(z-c_v)f_D(z)dz}{c_i} \tag{D.36}$$

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price after the actual damage revealed with the same objective function. Hence, she sets $p^{Flex} = \hat{d}$.

In t_2, the firms invest in the emission-free technology if the associated expected utility is positive. They anticipate that the Pigouvian carbon tax depends on the damage level that is not yet revealed. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned}
EU(\pi(\overline{\chi})) &= P\Big(p^{Flex} - c_v - c_i\overline{\chi} \mid c_v \leq p^{Flex}\Big) + P\Big(-c_i\overline{\chi} \mid c_v > p^{Flex}\Big) \\
&= \int_{c_v}^{\infty}(z-c_v)f_D(z)dz - c_i\overline{\chi} = 0 \\
&\longrightarrow \overline{\chi}^{Flex} = \frac{\int_{c_v}^{\infty}(z-c_v)f_D(z)dz}{c_i}
\end{aligned} \tag{D.37}$$

The emission-free production capacity equals the socially optimal level, as the carbon price set in t_3 equals the marginal damage ($p^{Flex} = \hat{d}$), i.e. $\overline{\chi}^{Flex} = \overline{\chi}^{Opt}$.

Commitment

In t_2, the firms make their investment decision given the announced carbon price level. In this setting, the firms know all parameters affecting their profits, such that the firms face no risk. However, the profit functions of firms depend on the carbon price level, and they have to distinguish two cases.

$$\pi(\chi) = \begin{cases} p - c_v - c_i\chi, & \text{for } c_v \leq p \\ -c_i\chi, & \text{else} \end{cases} \tag{D.38}$$

Given the indifference condition of the marginal firm investing in the emission-free technology:

$$\overline{\chi}^{Com} = \begin{cases} \frac{p^{Com} - c_v}{c_i}, & \text{for } c_v \leq p \\ 0, & \text{else} \end{cases} \tag{D.39}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision:

$$\max_p E[\mathcal{W}] = \begin{cases} \int_p^\infty Q(z)dz + (p - \mu_D)Q(p) & \\ \quad + \int_0^{\overline{\chi}(p)} \int_{-\infty}^\infty (t - c_v)f_D(t) - (c_i z)dtdz, & \text{if } c_v \leq p \\ \int_p^\infty Q(z)dz + (p - \mu_D)Q(p), & \text{else} \end{cases} \tag{D.40}$$

For the second case, is straightforward to show that the regulator sets carbon price equal to the expected damage. The solution for the first case is identical to the optimisation in (D.16). In both cases, the optimal carbon price equals the expected environmental damage and, thus,

$$p^{Com} = \begin{cases} \mu_D, & \text{if } c_v \leq p \\ \mu_D, & \text{else} \end{cases} \tag{D.41}$$

As by assumption the expected damage is higher than the variable costs, i.e., $\mu_D > c_v$, only the first case materialises. Thus, the optimal emission-free production capacity is equal to $\overline{\chi}^{Com} = \frac{\mu_D - c_v}{c_i}$.

CCfD

When the regulator offers a CCfD, she sets the carbon price in t_3 after the firms made their investment decision. Hence, she optimises (D.10), and the solution is identical with the one of the social planner and under *Regulatory flexibility*, i.e., $p^{CCfD} = \hat{d}$.

In t_2, the firms take their investment decision and account for the strike price of the CCfD. The carbon price is irrelevant to the firms. However, the firms only invest, if the strike price is above the variable costs.

$$\pi(\chi) = \begin{cases} p_s - c_v - c_i\chi, & \text{for } c_v \leq p_s \\ -c_i\chi, & \text{else} \end{cases} \longrightarrow \overline{\chi}^{CCfD} = \begin{cases} \frac{p_s - c_v}{c_i}, & \text{for } c_v \leq p_s \\ 0, & \text{else} \end{cases} \tag{D.42}$$

In t_1, the regulator chooses the strike price that maximises the expected social welfare:

$$\max_{p_s} E[\mathcal{W}] = \begin{cases} \int_p^\infty Q(z)dz + (p-\mu_D)Q(p) \int_0^{\overline{\chi}(p_s)} \int_{-\infty}^{\infty} (t-c_v) f_D(t) - (c_i z) dt dz, & \text{if } c_v \leq p_s \\ \int_p^\infty Q(z)dz + (p-\mu_D)Q(p), & \text{else} \end{cases} \tag{D.43}$$

For the second case, the strike price can take any realisation between zero and c_v, as firms would not invest. For the first case, the solution is identical to (D.30). Hence, the result is equal to

$$p_s = \begin{cases} \mu_D \\ 0 \leq p_s < c_v \end{cases} \tag{D.44}$$

Again, only the first case materialises, as by assumption $\mu_D > c_v$. Inserting p_s^{CCfD} into (D.42) shows that the investment level is equal to $\overline{\chi}^{CCfD} = \frac{\mu_D - c_v}{c_i}$.

Welfare ranking

As shown before, the carbon price and the emission-free production capacity are identical in the social optimum and under *Regulatory flexibility*. Thus, welfare in this carbon pricing regime is identical to the social optimum, i.e., $E[\mathcal{W}_{\sigma_D}^{Opt}] = E[\mathcal{W}_{\sigma_D}^{Flex}]$.

To compare *Flex* and *CCfD*, we evaluate the difference of expected welfare. Since $p^{Flex} = p^{CCfD}$, there is only a difference regarding welfare from production with the emission-free technology. Taking the derivatives of (5.19), we see that the expected social welfare is increasing in investments as long as $\overline{\chi} \leq \overline{\chi}^{Opt} = \overline{\chi}^{Flex}$:

$$\begin{aligned} \frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} &= \int_{c_v}^{\infty} (z-c_v) f_D(z) dz - c_i \overline{\chi} > 0 \; \forall \, \overline{\chi} < \frac{\int_{c_v}^{\infty} (z-c_v) f_D(z) dz}{c_i} \\ \frac{\partial^2 E[\mathcal{W}]}{\partial \overline{\chi}^2} &= -c_i < 0 \end{aligned} \tag{D.45}$$

As $\overline{\chi}^{CCfD} \leq \overline{\chi}^{Flex}$, we conclude that $E[\mathcal{W}_{\sigma_D}^{Flex}] \geq E[\mathcal{W}_{\sigma_D}^{CCfD}]$.

Lastly, it is straightforward to show that *Commitment* is welfare-inferior to the *CCfD* regime. As investments are identical in both regimes, the difference in welfare stems form the consumer surplus. Again, applying Jensen's inequality, it holds that

$$E[\mathcal{W}_{\sigma_D}^{CCfD}] - E[\mathcal{W}_{\sigma_D}^{Com}] = E[\int_{D}^{\infty} Q(z)dz] - \int_{\mu_D}^{\infty} Q(z)dz \geq 0. \tag{D.46}$$

D.5. Regulatory solutions with variable cost risk and potentially socially not optimal production

Under variable cost risk and potentially welfare-reducing production, the increase in marginal production costs might be so high that firms using the emission-free technology do not produce in t_4. As the investments in abatement are sunk, they do not impact the production decision. Overall welfare in t_4 is given by:

$$\mathcal{W} = \begin{cases} \int_p^{\infty} Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}}(d - \hat{c_v} - c_i z)dz, & \text{for } \hat{c_v} < d \\ \int_p^{\infty} Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz, & \text{for } \hat{c_v} \geq d \end{cases} \tag{D.47}$$

Social optimum

In the social optimum, the social planner sets the carbon price p^{Opt} after the level of variable costs revealed. The optimisation is identical to maximising (D.10). Hence, it holds that $p^{Opt} = d$. The social planner sets the emission-free production capacity $\overline{\chi}^{Opt}$ such that it maximises expected welfare:

$$\begin{aligned} \max_{\overline{\chi}} E[\mathcal{W}] =& P\left(\int_p^{\infty} Q(z)dz + (p-d)Q(p) + \int_0^{\overline{\chi}}(d - c_v - c_i z)dz \mid c_v \leq d\right) \\ =& \int_p^{\infty} Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz + P((d-c_v)\overline{\chi} \quad \mid c_v < d) \\ =& \int_p^{\infty} Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}}(c_i z)dz + \int_{-\infty}^{d} (d-z)\overline{\chi} f_{C_v}(z)dz \end{aligned} \tag{D.48}$$

We solve the problem using the first-order conditions:

$$\begin{aligned} \frac{\partial E[\mathcal{W}]}{\partial \overline{\chi}} =& - c_i \overline{\chi} + \int_{-\infty}^{d} (d-z) f_{C_v}(z)dt = 0 \\ \longrightarrow \overline{\chi}^{Opt} =& \frac{\int_{-\infty}^{d} (d-z) f(z)dt}{c_i} \end{aligned} \tag{D.49}$$

The integral of the distribution function represents the marginal benefit from abatement (damage minus variable costs) weighted by its probability of realisation. The integral is limited to d as beyond this point production does not occur and the marginal benefit, hence, is zero.

Regulatory flexibility

As under the assumption of a social planner, the regulator sets the carbon price after the firms made their investment. Hence, she optimises (D.23) and sets $p^{Flex} = \hat{d}$, which is the Pigouvian tax.

In t_2, the firms choose to invest if their expected utility is greater than zero, given the risk regarding its future variable costs and anticipating the Pigouvian carbon tax rational of the regulator. The marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= P\Big(p^{Flex} - c_v - c_i\overline{\chi} \mid c_v \leq p^{Flex}\Big) + P\Big(-C(\overline{\chi}) \mid c_v > p^{Flex}\Big) = 0 \\ &= \int_{-\infty}^{d} (d-z) f_{C_v}(z)dz - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{Flex} &= \frac{\int_{-\infty}^{d}(d-z)f_{C_v}(z)dz}{c_i}, \end{aligned} \tag{D.50}$$

where we inserted the optimal carbon price ($p^{Flex} = d$). As in the case of damage risk without risk aversion, *Regulatory flexibility* reaches the social optimum.

Commitment

Under *Commitment*, the firms choose to invest after the regulator has announced the carbon price. The rationale for investments is identical to the one of *Regulatory flexibility*, as no damage risk exists. Hence, the structural solution is identical with one under the flexible carbon price regime.

$$\overline{\chi}^{Com} = \frac{\int_{-\infty}^{p}(p-z)f_{C_v}(z)dz}{c_i} \tag{D.51}$$

In t_1, the regulator sets the carbon price anticipating that her choice impacts the firms' investment decision:

$$\begin{aligned} \max_p E[\mathcal{W}] &= \int_p^{\infty} Q(z)dz + (p-d)Q(p) - \int_0^{\overline{\chi}(p)} (c_i z)dz + \int_{-\infty}^{p} \overline{\chi}(d-t)f_{C_v}(t)dt \\ &\longrightarrow p^{Com} = d \end{aligned} \tag{D.52}$$

The result is identical to the one of *Regulatory flexibility* and the social planner. As the firms are not risk averse, the regulator chooses the Piguvian tax level, that they can perfectly anticipate.

CCfD

When the regulator can offer firms a CCfD in t_1, she sets the carbon price in t_3 after the actual variable costs revealed and the firms made their investment decision. The firms using the emission-free production technology produce, if their variable costs are lower than the conventional technology, i.e., if $c_v < p_s$. The solution yields the socially optimal Pigouvian tax, i.e. $p^{CCfD} = d$. In t_2, the firms invest in the emission-free technology given the announced strike price. The costs remain risky, hence the marginal firm investing in the emission-free technology is characterised by:

$$\begin{aligned} EU(\pi(\overline{\chi})) &= P\Big(p_s - c_v - c_i\overline{\chi} \mid c_v \leq p_s\Big) + P\Big(-c_i\overline{\chi} \mid c_v > p_s\Big) = 0 \\ &= \int_{p_s}^{\infty} (p_s - z) f_{C_v}(z) dz - c_i\overline{\chi} = 0 \\ \longrightarrow \overline{\chi}^{CCfD} &= \frac{\int_{-\infty}^{p_s} (p_s - t) f_{C_v}(z) dz}{c_i} \end{aligned} \tag{D.53}$$

In t_1, the regulator chooses a strike price that maximises expected welfare. She accounts for the firms' reaction to the strike price:

$$\begin{aligned} \max_{p_s} E[\mathcal{W}] &= \int_{p}^{\infty} Q(z)dz + (p-d)Q(p) - \int_{0}^{\overline{\chi}(p)} (c_i z)dz + \int_{-\infty}^{p_s} \overline{\chi}(d-t) f_{C_v}(t) \\ \longrightarrow p_s &= d \end{aligned} \tag{D.54}$$

Welfare ranking

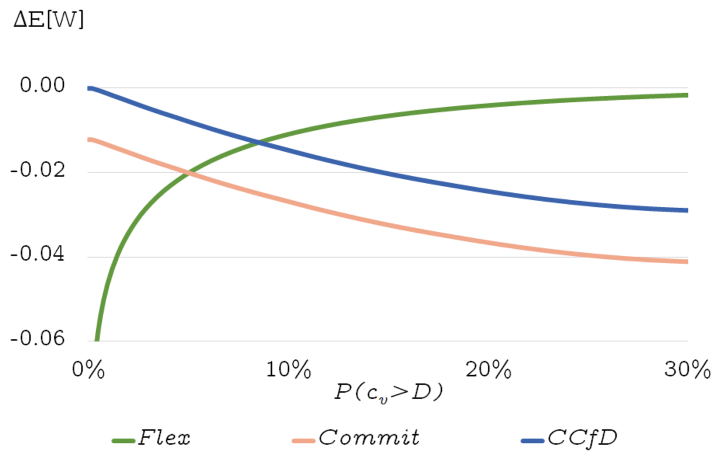
As all carbon pricing regimes result in the socially optimal carbon price and emission-free production capacity, there is no difference in welfare. The absence of risk aversion in this setting leads to equivalent welfare expectations.

D.6. Welfare difference compared to the social optimum in the presence of damage risk, and (ex post) potentially socially not optimal abatement due to an increase in σ_D

Figure D.1 shows a similar effect, when varying the probability of socially not optimal production, $P(C_v > D)$, by altering the expected value of the marginal damage, μ_D.

The welfare of *CCfD* and *Commitment* is not affected by the presence of risk aversion (compare Figure D.1 (with risk aversion) with Figure 7b (no risk aversion)). Hence, as explained in section 4.2, the shortfall in welfare increases with an increased probability of socially not optimal production. Furthermore, the effect is concave in the probability of socially not optimal emission-free production as the welfare-deferring effect is mitigated by decreasing socially optimal investments.

The *Regulatory flexibility* regime does not result in the social optimum if the firms are risk averse. However, as the socially optimal emission-free production capacity decrease, the absolute gap in welfare compared to the social optimum decreases.



$D \sim N(\mu_D \in [4.25; 5.5], \sigma_D^2 = 0.25)$, $\lambda = 1.5$, $Q(p) = 5 - 0.1p$, $c_v = 4$, $c_i = 1$.

Figure D.1.: Difference in welfare compared to social optimum due to change in $P(c_v > D)$ by altering μ_D in the presence of damage risk and potentially welfare-reducing production.

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