CHARLES UNIVERSITY

FACULTY OF SOCIAL SCIENCES

Institute of Political Studies

Department of Political Science

Bachelor's Thesis

2023 **Til Gosch**

CHARLES UNIVERSITY

FACULTY OF SOCIAL SCIENCES

Institute of Political Studies

Department of Political Science

The Influence of Exogenous Price Shocks on the Functioning and Efficiency of Environmental Instruments

Bachelor's Thesis

Author of the Thesis: Til Gosch

Study programme: Philosophy, Politics & Economics

Supervisor: PhDr. Jiří Schwarz

Year of the defence: 2023

Declaration

1. I hereby declare that I have compiled this thesis using the listed literature and resources only.
2. I hereby declare that my thesis has not been used to gain any other academic title.
3. I fully agree with my work being used for study and scientific purposes.

In Prague on the 1st of May 2023 Til Gosch

References

GOSCH, Til. *The Influence of Exogenous Price Shocks on the Functioning and Efficiency of Environmental Instruments.* Praha, 2017. 59 pages. Bachelor's thesis (Bc). Charles University, Faculty of Social Sciences, Institute of Political Studies. Department of Political Science. Supervisor PhDr. Jiří Schwarz, Ph.D.

Length of the Thesis: 108.341 characters

Abstract

This paper investigates the European Emission Trading Scheme (EU-ETS), examining allowance price drivers and consequences for regulated companies and proposing an incentive-based adaptation to its current design. Through literature review and data analysis, I identify the global energy crisis, institutional decisions, and tighter regulations as key factors influencing allowance price surges. The consequences for companies show no evidence of negative effects on competitiveness, carbon leakage, or investment leakage, mainly due to low prices in the chosen sample period. However, the Porter Hypothesis, which predicts a positive impact on productivity by environmental regulation, is unsupported by the literature. The proposed incentive-based approach employs a market-based subsidy for emission reductions beyond the efficient level, demonstrating the potential for enhancing productivity and reducing emissions. While the incentive-based approach shows promise in reducing emissions and promoting productivity-enhancing innovations, it faces limitations, particularly regarding real-world applicability. Further research is needed to evaluate the applicability of the proposed instrument in achieving EU climate objectives while enhancing industrial productivity.

Keywords

EU-ETS, Porter Hypothesis, Innovation, Marginal Abatement Costs, Environmental Economics

Title

The Influence of Exogenous Price Shocks on the Functioning and Efficiency of Environmental Instruments

Acknowledgement

I want to express my gratitude to my supervisor PhDr. Jiří Schwarz for guiding and helping me to write this thesis, and my family and friends for standing by my side and providing me with valuable ideas. I also want to express special gratitude to Elizabeth Burns for supporting me in all situations.

Table of Contents

List of Figures

Introduction

Carbon must have its price - because nature cannot pay this price anymore.

- *Ursula von der Leyen (2020)*

This sentiment was conveyed during Ursula von der Leyen's State of the Union address in September 2020, where she announced the establishment of the Carbon Border Adjustment Mechanism (CBAM). The CBAM is a further step by the European Union (EU) towards combating climate change, which has become one of the most pressing challenges of our time. The European Emission Allowance Trading Scheme (EU-ETS) already represents a distinct cap-and-trade mechanism established to regulate the release of carbon dioxide emanating from industrial and energy infrastructures across Europe. Despite the system's proven potential to reduce European emissions, critical voices are emerging within the Union that fear the impact the EU-ETS will have on regulated companies based in the EU. These critical voices stem from the exponential price development of EU allowances (EUAs), which has been observed since the beginning of 2021 and originates in energy price developments and institutional decisions. The literature on the corporate impact of these price developments is limited. Existing studies focus in particular on possible distortions of competition, migration of companies to less regulated foreign countries (carbon leakage) and entrepreneurial investments. Although the existing literature gives the all-clear to concerns about negative consequences, the results can only be applied to the current situation to a limited extent, as all studies focus on periods in which EUA prices were very low. Therefore, the rapid price increase has reignited the discussion and concerns about negative impacts and the EU's competitiveness in the global market. The question arises: if nature can no longer pay the carbon price, how long can and will companies continue to pay this price?

This thesis aims to add to the existing discourse about mitigating emissions of greenhouse gases while avoiding placing excessive burdens on both businesses and consumers. Several authors have already investigated the potential of financial incentives in reducing climate-damaging greenhouse gases in the past. Fischer and Newell (2008), for example, examined various policies that can potentially drive greenhouse gas reductions and found that a well-designed subsidy is suitable for driving innovation in low-carbon and climate-friendly technologies. Böhringer and Rutherford (2008) analysed the potential effectiveness of combining bottom-up and top-down approaches to climate change policy, including subsidies for low-carbon technologies. They found subsidies effective for combating emissions, especially when combined with existing instruments such as certificate trading. With the model of a market-based subsidy, the thesis is also located in the study of financial incentives for environmental-economic problems. It is intended to contribute to the discussion on regulatory adjustments to the EU-ETS.

Thus, the research question of this thesis revolves around whether a market-based subsidy in combination with the already established emissions certificate trading can contribute to achieving the ambitious climate targets without burdening the regulated companies too much. To answer this question, some hypotheses must first be examined. To begin with, it is necessary to clarify the causes behind the rapidly rising EUA prices. It seems reasonable to assume that the price increase can be attributed to an exogenous energy price shock. The paper analyses the hypothesis of whether this exogenous shock is the leading cause of price increases. Subsequently, the theory has to be examined to determine whether carbon pricing implemented in the European cap-and-trade system has negative consequences for regulated companies and what these consequences are in detail. These hypotheses need to be examined to clarify whether an EU-ETS adjustment is necessary and how it should be designed.

This work aims to extend the existing framework of the EU-ETS and consider the possibility of a combination of tradable emission certificates and subsidies. The aim is not to obtain a perfectly developed model for emissions regulation at the end of the work but to have a simplified representation that can be used to initiate further scientific investigations. This simplified model should incentivise all stakeholders within the EU to discuss this possible regulatory adjustment further, investigate the assumptions behind it more deeply and find fertile ground for future regulatory adjustments.

A marginal cost approach is chosen to design the proposed subsidy model. The consideration of environmental-economic problems under the magnifying glass of marginal environmental damage and marginal abatement costs is an approach that is widespread in environmental economics. For the environmental-economic foundations of the model, the fundamental research by Perman et al.(2003) is used. The inspiration for a market-based subsidy or effluent charge comes from Kwerel (1977), who puts forward a similar proposal to solve the problem of imperfect information in determining the cost optimum in environmental-economic issues. The model he proposes is placed in a new problem context, extended by additional assumptions, and checked for its corporate and societal benefits.

The thesis is structured as follows. In the first chapter, the regulatory framework of the EU-ETS is explained. Since the EU-ETS is a complex environmental regulation, only the essential functions and key points will be touched upon here. Subsequently, the EU-ETS is examined against the background of the current energy crisis, the rapid price developments are illustrated, and possible price drivers and fundamentals of the allowances are identified. Identifying these drivers should be considered in future discussions on regulatory adjustments. The second chapter examines the consequences of carbon pricing for companies. In particular, the distortion of competition, the migration of companies to less regulated areas, and investment decisions are relevant. In the third chapter, the adaptation to the EU-ETS is presented. The model's core is a market-based subsidy paid out for emission savings above the efficient level. Following the third chapter, a discussion section will examine the model's limitations and provide an outlook on possible further research on the proposed model.

Methodology

Exogeneity of Energy Price Shocks

For this thesis, the prices of energy goods are considered exogenous to the determination of CO_2 prices. This assumption is based on the studies of other authors who examined the drivers of carbon prices and characterised various variables such as energy prices, weather, or financial markets as exogenous influences.

Beat Hintermann (2010) analyses the drivers of allowance prices in the first phase of the EU-ETS. The author posits the exogeneity of coal and gas prices in relation to allowance prices. While the prices are determined simultaneously on international markets, technically making it incorrect, Hintermann (2010) explains that any potential bias introduced should be minor. In their econometric analysis of price determination in the EU-ETS, Aatola et al. (2013) also assume several variables, such as coal, oil, gas, or German electricity, as exogenous to the dependent variable allowance price. Chevallier (2012) examines the relationship between the market prices of EU-ETS allowances and energy commodity prices such as oil, gas, coal, or electricity. He assumes the energy prices to be exogenous to the carbon prices and mathematically excludes cross-correlations between the variables. Julien Chevallier (2011) analysed in a prior publication investigating the propagation of global perturbations to EUA spot, EUA futures, and CER futures carbon prices, utilising a comprehensive data set encompassing 115 indicators on macroeconomics, finance, and commodities. Based on these findings, the influences of the global energy crisis of 2020-23 are also considered to be exogenous.

This terminological twist is not necessarily relevant for the further discussion of the proposed model but should nevertheless be explained to avoid confusion in the following pages.

Literature Review & Data

For the first two chapters, I have chosen to focus my research mainly on a literature review and to support it with data. Especially for the first chapter, it is possible to prove the correlation between EUA prices and different price drivers, such as gas prices or extreme weather events, with empirical models. Authors such as Aatola et al. (2013), Batten et al. (2021), and Mansanet-Bataller (2021) certainly perform such calculations. For this paper, however, it is sufficient to cover this with an extensive literature review. After all, the thesis focuses primarily on proposing an alternative model to the current EU emissions policy and not on the correlation between EUAs and energy prices.

Marginal Cost Perspective

I have employed a marginal cost framework to simulate the proposed subsidy program within the environmental-economic context. This approach is the most suitable, as it can illustrate environmental-economic problems and allows the determination of cost-efficient equilibria in the simplest way. Due to the simplified representation and the assumptions made in the model, the applicability of the model is often questioned in the environmental economics literature (see Chapter Four). However, since this paper does not aim to present a fully developed model, it is sufficient to demonstrate the subsidy as a marginal cost approach. For the basics of the model, the illustrations from the primary research by Perman et al. (2003) are used and adapted for my purposes. The model of the market-based subsidy is based on the proposal by Kwerel (1977), who also uses a marginal cost approach. The author proposes an effluent charge in combination with tradable emission permits to solve the problem of imperfect information in determining marginal abatement costs. The model of Kwerel (1977) is considered in a new problem context and extended with assumptions.

1 Effects of the Global Energy Crisis on Carbon Prices

The European Union Emissions Trading System (EU-ETS) was the first environmental instrument to use a cap-and-trade system to limit emissions from European industry to protect the global climate. The emission rights of European companies are limited and tradable. With the introduction of these tradable emission rights, the world's first market for emissions has developed in the EU area. The functioning of the EU-ETS is further explained in section 1.1. However, as a tradable commodity, EUAs are also vulnerable to exogenous shocks. This was particularly evident during the global energy crisis of 2021-23. In 2023, after recuperating from the ramifications of the COVID-19 pandemic, the global community finds itself amid a worldwide energy crisis typified by exorbitant costs for energy commodities such as oil, natural gas, and electricity (See Section 1.2 and International Energy Agency, 2022c). While similar price levels occurred before in the case of oil shocks, „there is no precedent for the price levels seen in 2022 for natural gas" (International Energy Agency, 2022c). Even though prices are no longer at the highs they reached during the crisis, they remain well above pre-pandemic levels (see section 1.2). These global price developments profoundly impact the economy and companies' energy production and use. The prices of energy significantly influence the utilisation of fossil fuels for electricity production. The 2021-23 energy crisis and the rise in the price of natural gas increased global demand for coal. Within the power industry, elevated gas prices resulted in a transition in the merit order from gas to coal, signifying that energy suppliers have shifted their preference from utilising gas-fired to coal-fired power plants for electricity generation. This phenomenon is referred to in the literature as fuel switching and is discussed in more detail in section 1.3.1. With a gas-to-coal switch, the emissions of the energy sector also increase. Within the framework of the EU-ETS cap-and-trade mechanism, demand for European Union Allowances (EUAs) increases while the supply remains constant. Section 1.3 analyses the price developments of EU-ETS allowances that have taken place due to this demand-supply relationship. In addition, other price fundamentals of the EUAs, such as weather and institutional decisions, are examined in section 1.3.

1.1 The Framework of the EU Emission Trading System

1.1.1 Coverage of the EU-ETS

The EU-ETS covers various sectors and several specific greenhouse gas emissions. Geographically, the EU-ETS covers all 27 members of the EU and the entire European Economic Area (EEA), as well as the Economic Free Trade Association (EFTA) countries, which includes Liechtenstein, Norway and Iceland (European Commission, 2022, p. 4). In 2017, an agreement was reached between the EU and the Swiss Confederation to interconnect their respective Emission Trading Systems (European Union, 2017).

In its first phase (2005-2007), the trading scheme only covered CO_2 emissions in the power and manufacturing industry. Since Phase III (2013-2020), the EU-ETS covers CO_2, N_2O and PFC emissions (European Commission, 2022). The Swiss ETS encompasses a broad range of other greenhouse gases added to those specified by the EU (CO2 Ordinance, 2012/2023-01-01).

Regarding the economic sectors, the EU-ETS, as well as the Swiss ETS, regulate emissions from electricity and heat generators as well as manufacturing installations. They also cover the aviation sector limited to flights within the European Economic Area (EEA), Great Britain and Switzerland (European Commission, 2022). The sectors covered account for „around 36% of all EU emissions" (European Commission, 2022, p. 5).

1.1.2 Cap on Emissions

The EU-ETS sets an upper limit (cap) on the quantity of greenhouse gas emissions companies are permitted to release. The holder of an emission allowance is permitted to emit „one tonne of carbon dioxide (CO2) or the equivalent amount of other powerful greenhouse gases, nitrous oxide (N2O) and perfluorocarbons (PFCs)" (European Commission, 2021a). The caps on emissions are separately set for stationary installations in energy production, manufacturing, and aviation. In Phase IV (2021-2030), both caps for aviation and stationary installations decrease by 2.2% each year to achieve the EU's emission reduction target (European Commission, 2022, p. 6).

1.1.3 Auctioning of Emission Allowances

The allocation of allowances in Phase IV of the EU Emissions Trading System predominantly relies on the auctioning mechanism, constituting 57% of the total emissions cap (European Commission, 2022). The auction takes place on the EEX, the European Energy Exchange AG, appointed by the European Commission as the official distributor of allowances in 2021. According to the Commission Regulation (2010), this platform is the best and most cost-effective way to secure an open, transparent, non-discriminatory distribution.

The auction clearing price is specified in Commission Regulation No 1031/2010. The determination of the clearing price takes place upon closing the bidding window. The auctioning platform EEX sorts all submitted bids according to the price bid. After that, the volumes for which the participants have bid shall be added up, starting with the highest bid. The bid price where the added volume matches or exceeds the emission cap determines the market-clearing price for allowances (European Union, 2010).

Commission Regulation No 1031/2010 provides additional explanations regarding the temporal sequencing, implementation, and various other facets of auctioning emission allowances (European Commission, 2022).

1.1.4 Free Allocation of Allowances

Even though the major distribution method for EU-ETS allowances is auctioning, a large share of allowances is allocated freely to the sectors specified in 1.1.1. The reason for this policy is to mitigate the potential carbon leakage, a phenomenon whereby carbon-intensive industries relocate their operations to jurisdictions outside the EU with less stringent emission regulations to avoid the costs associated with carbon allowances. Such actions can potentially increase overall global emissions of greenhouse gases, which runs counter to the objectives of reducing carbon emissions and combating climate change (European Commission, 2022). In Chapter 2.3, the problem of carbon leakage will be reviewed.

The distribution of free allowances is based on performance benchmarks. Within each industry sector, the benchmarks vary and correspond to the emission intensity of producing a single unit of the top 10% of installations with the lowest emissions. These benchmarks are gradually lowered to enhance the motivation for decarbonisation and encourage the development of innovative solutions (European Commission, 2022), which is why the European Commission decided to adjust the benchmark for companies in 2021 (European Union, 2021). These benchmarks are intended to incentivise the decarbonisation of the European industry by rewarding the top performers in each sector with free allowances and encouraging other operators to decrease their emissions (European Court of Auditors, 2020).

The EU has delineated 63 sectors and sub-sectors, which account for 94% of the total industrial emissions within the EU. These sectors are deemed at greater risk of carbon leakage and, as such, are considered eligible to fully cover their benchmark products by free allowances (European Commission, 2022; European Court of Auditors, 2020; European Union, 2019a). For industrial operators not included in the list, 80% of allowances were allocated for free in 2013, slowly decreasing to 30% in 2020 (European Court of Auditors, 2020, p. 11). In 2021, the EU announced that in Phase IV of the EU-ETS (2021-2030), the volume of freely allocated allowances would be linked to operators' productivity. Accordingly, there will be changes in the volume in case productivity increases or decreases by 15% (European Commission, 2022, p. 11; European Union, 2019b).

1.2 Global Energy Price Development

To better grasp the global development of energy prices between 2021 and 2023, section 1.2 will analyse the development of Brent Crude Oil prices and the natural gas prices for the EU provided by the Federal Reserve Bank of St. Louis and Refinitiv Eikon. Figure 1 and Figure 2 show the respective price developments.

Figure 1 shows the development for the price of Brent Crude Oil for the European Region in U.S. Dollars per Barrel. With the onset of the global COVID-19 Pandemic, prices for crude oil in Europe fell sharply. The sharpest drop in oil prices occurred between the beginning of March and the end of April, where the prices dropped 73% in total before rising again. Pre-pandemic prices were reached again in March 2021 and continued to grow. The sharpest price increase was observed with Russia's attack on Ukraine, where prices climbed 39% between late February and early March to their all-time high of US$133 per barrel. After that, prices fell until they rose again in the summer of 2022, reaching peak prices of 129 US dollars per barrel. Since then, oil prices have fallen again but remain volatile. The January 2023 price level is only 22.5% above the pre-pandemic level.

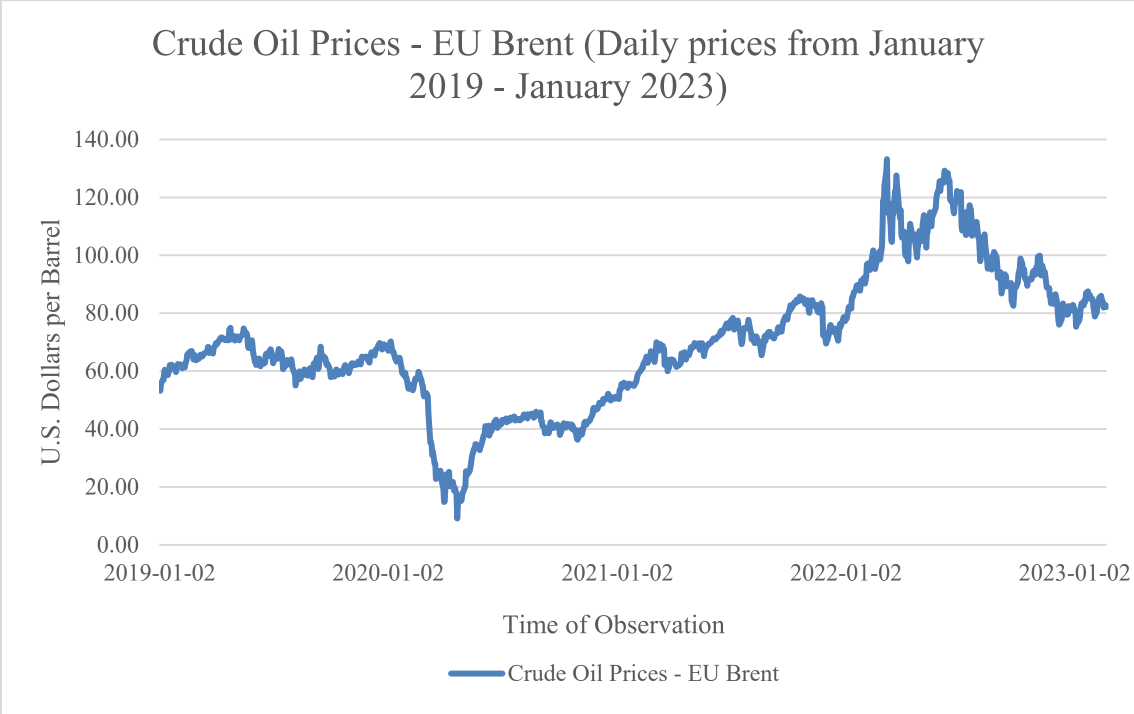

Figure 1: Prices for Crude Oil - Europe Brent in U.S. Dollars per Barrel (January 2019 - January 2023)
Source: Federal Reserve Bank of St. Louis

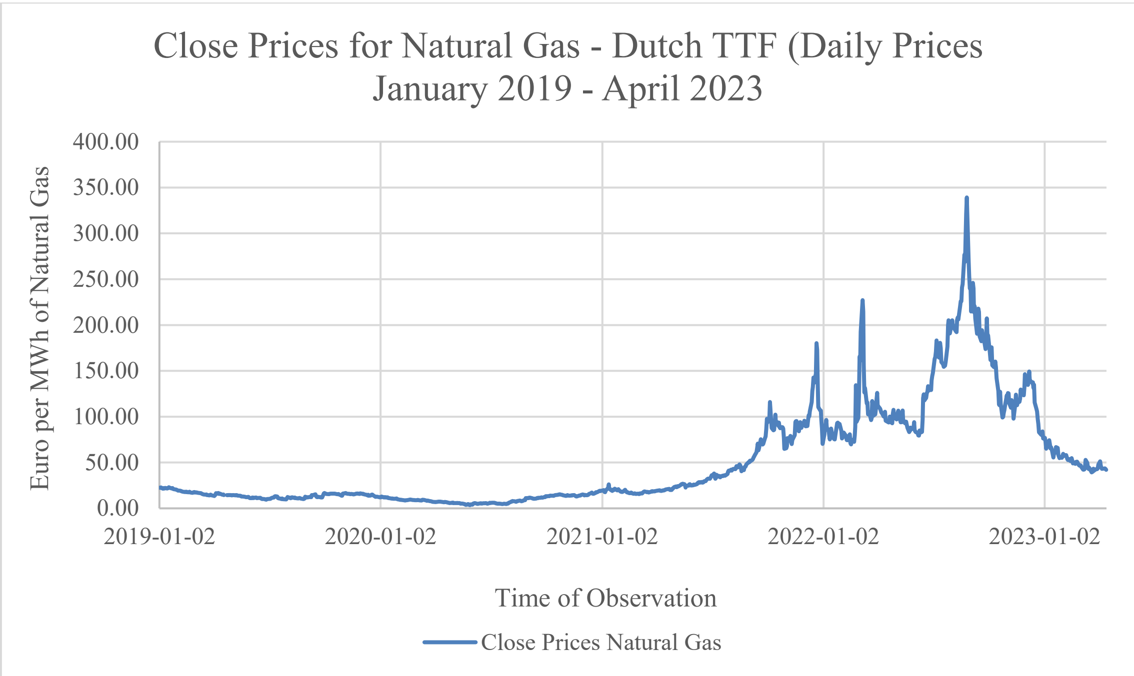

Figure 2: Close Prices for Natural Gas (Dutch TTF Futures January 2019 - January 2023) in Euro per MWh
Source: Refinitiv Eikon

Figure 2 shows the respective development for prices for natural gas in Euro per MWh. Similar to the results of crude oil prices, the European prices for natural gas dropped in the first half of 2020. Between January and June 2020, prices fell by 66%. In July 2020, prices started to rise again, and in September 2020, natural gas prices returned to pre-pandemic levels. This means gas prices reached this level much earlier than crude oil prices. With the start of the war in Ukraine, prices increased, reaching a peak of +255% between the 23rd of January and the 7th of March 2022. Prices for natural gas reached an all-time high of almost 339 Euros per MWh on the 26th of August 2022. Gas prices have been moving downwards since then and, in January 2023, are below the price level of September 2021, but overall gas prices are still 190% above pre-pandemic levels.

In summary, natural gas prices are significantly more inflated than crude oil prices and remain significantly higher than oil prices. The following sections are devoted to answering the first hypothesis, i.e. whether the energy price changes presented here drive the rising EUA prices or whether other price fundamentals affect the European carbon price.

1.3 Energy Prices, Electricity Production and Fuel Switching

The global price spikes observed since 2021 impact fossil fuel use and macroeconomic and microeconomic effects. The composition of a country's energy mix is based on the prices for the respective energy sources. One phenomenon that deserves special mention here is *fuel switching*. Fuel switching refers to the capacity and ability of electricity producers to switch from an expensive energy source to a cheaper one when generating electricity. The term fuel switching can be misleading and give the impression that power plants can change the fuel used to generate electricity or quickly switch different power plants on and off. The undercurrent of this section refers to switching between different types of power plants, e.g. coal-fired and gas-fired. Each power plant has different marginal costs of operation. Not all power plants of one kind necessarily have the same marginal costs. Aspects such as efficiency differences can also influence these marginal costs (see Bertrand 2014).

The so-called merit order is obtained if the different power plants, such as renewables (solar, wind, hydro), coal and gas, are arranged in ascending cost. A country's electricity mix is based on this merit order, and the price agreed on the electricity exchange markets is always based on the most expensive power plants necessary to cover the electricity demand. The intuitive idea behind fuel switching is that due to high carbon prices, electricity generation with emission-intensive coal becomes so expensive that gas-fired power plants swap places with coal-fired power plants in the merit order. This would mean that significantly fewer emissions would be released in the power sector in the case of coal-to-gas fuel switching, and thus fewer carbon allowances would be demanded. Less demand for EUAs, in turn, implies lower EUA prices.

1.3.1 Fuel Switching under Carbon Regulation

Especially since the introduction of the EU-ETS, fuel switching has attracted new interest in research. The regulatory increase in carbon prices has made fossil fuels more expensive and forced operators to look for alternatives, especially in power generation. One topic often explored in the literature is how carbon prices accelerate the switch from emission-intensive lignite and hard coal to renewables or much lower-emission natural gas.

For instance, Delarue et al. (2008) use empirical data to determine the fuel-switching behaviour of power plants. The data show that in the summer of 2005, fuel was switched from coal to gas in the first phase of the EU-ETS. Next, the authors use an electricity generation model to determine the effect of the EU-ETS allowance prices on fuel switching in the summer of 2005 and the potential emission savings that can be achieved by fuel switching under an assumed equilibrium allowance price. Wilson and Staffell (2018) examine the significant drop in carbon emissions in the UK in 2016. The authors argue that the reduction is not due to the expansion of renewables or nuclear power but that this effect can be attributed to fuel switching from coal to gas. Wilson and Staffel's (2018) research findings suggest that the substitution of coal with natural gas resulted in a per-capita annual reduction of 400 kg of CO_2 emissions between 2015 and 2016, amounting to 6% of the national emissions.

Furthermore, Wilson and Staffell (2018) investigate which circumstances have led to fuel switching and, thus, to lower emissions in the UK power sector. In addition to the government's political will to actively reduce emissions, the drivers include the ability and capacity of plant operators to switch quickly from coal to gas-fired power plants. The authors conclude that both were present in the UK in 2016. However, they attribute the most significant effect to the carbon pricing of the UK Carbon Price Support (CPS) policy. An effective carbon price made coal so expensive that power operators in the UK switched 15% of their energy mix and instead used cheaper and lower-emission natural gas to produce electricity. Bertrand (2014) investigates coal-to-gas fuel switching of heterogeneously efficient power plants under the EU-ETS and how the efficiency of a power plant affects the cost of fuel switching. The author comes to three main conclusions. First, the marginal costs of a power plant switching to a different fuel are increasingly dependent on gas prices as the effort for fuel switching increases. This finding is fascinating among the price developments for natural gas estimated in 1.1. Second, Bertrand (2014) shows that the impact of gas prices on carbon prices (discussed further in 2.3.1) depends on uncontrolled carbon emissions. Uncontrolled here refers to emissions from power plants that have not yet been removed. When these uncontrolled emissions are high, the effort for fuel switching increases, making gas prices more prominent in the marginal cost of fuel switching and, thus, playing a more significant role in carbon prices. Thirdly, Bertrand (2014) emphasises that the timing of the fuel switching also matters, i.e. whether it is at the end of an EU-ETS phase or the beginning.

1.3.2 The Energy Crisis and Coal Consumption

The literature has shown that there is indeed fuel switching from coal to gas under the EU-ETS, but this switch also depends on natural gas prices. Against the background of the gas price development in Europe, the question arises of how the use of fuels for electricity production has changed. Intuitively, coal-fired, and gas-fired power plants will swap places again in the merit order when gas prices rise. Increasing the use of coal as a fuel for electricity generation will have a higher demand for emission certificates, which will cause the carbon price to rise.

The effect of high oil and gas prices on electricity generation is not necessarily straightforward. *Ex-ante* studies by van Ruijven and van Vuuren (2009) clarify that higher gas prices have two opposing effects. On the one hand, high prices create incentives to invest in renewable, carbon-neutral energy and energy efficiency, as the cost difference to fossil fuels decreases (van Ruijven & van Vuuren, 2009; Vielle & Viguier, 2007). On the other hand, an increase in gas prices can also cause a fuel switch to coal-based power generation. Carbon prices and climate policy play an important role. The authors use the global energy model TIMER to determine under which conditions a switch to coal or renewables can be expected and come to two elementary conclusions. First, in the absence of climate policy, high prices of hydrocarbon fuels can result in a shift towards coal utilisation, thereby leading to an increase in carbon emissions (van Ruijven & van Vuuren, 2009) and second, with climate policy and high carbon prices, electricity generation will switch from natural gas to coal-based energy with carbon capture and sequestration (CCS), nuclear and wind.

The conclusions of van Ruijven and Van Vuuren (2009) are supported by analyses of coal use and renewables during the 2021-23 energy crisis by the International Energy Agency (IEA). According to the Coal Report 2022, global coal consumption reached an all-time high in 2022, exceeding 8 billion tonnes. „The largest increase in coal demand this year is expected in India (+7%/+70 Mt), followed by the European Union (+6%/+29 Mt) and China (+0.4%/+18 Mt)" (IEA, 2022a, p. 11). The use of coal in the EU has steadily declined over the last decade, reaching a low point with the decline in economic activity during the Corona pandemic in 2020. In the following year, 2021, gas prices spiked (see section 1.1), and coal experienced an upswing in competitiveness with gas despite higher carbon allowance prices. Coal consumption in the EU will increase by 14% in 2021. The situation worsened in 2022 with the Russian invasion of Ukraine, reducing the gas supply and further inflating gas prices. According to the IEA's preliminary analysis, coal consumption in the energy sector increased by 9% (31 Mt) in 2022, approaching pre-pandemic levels. The IEA nevertheless forecasts that total coal demand will fall from 478 Mt (2022) to 371 Mt by 2025, although uncertainties may influence these projections in the gas market (IEA, 2022a).

At the same time, in line with van Ruijven and Van Vuuren's (2009) findings, rising energy prices have also increased the attractiveness of renewable energy projects. The Russian invasion of Ukraine further accelerated this motivation and led to ambitious targets by member states and the Union. In 2022, the European Commission unveiled the REPowerEU strategy, an initiative to elevate the proportion of renewable energy sources in the European energy mix to 45% by 2030, surpassing the previously agreed-upon target of 40%. Meeting this objective necessitates the installation of nearly 600 GW of solar photovoltaic (PV) systems and 510 GW of wind power capacity by the year 2030 (IEA, 2022b). The IEA forecast expects renewable energy to grow by almost 60% (+425 GW) between 2022 and 2027, more than twice the growth between 2016 and 2021. The IEA is sceptical that the 45% renewable energy target can be reached by 2030. Further policy improvements, such as restructuring auction mechanisms and incentive systems, are needed to achieve this ambitious target.

1.4 EU-ETS Allowance Drivers & Price Fundamentals

The 2021-23 energy crisis and the resulting high prices for natural gas have led to more robust demand for coal as a fuel. With gas-to-coal fuel switching, emissions in the energy sector also increase, and the demand for emission allowances increases. Since the EU fixes the quantity of allowances, this must intuitively lead to higher market prices. It is, therefore, worth analysing the prices of EUAs over time.

Figure 3: Price Development EUA and Californian Cap and Trade Program (03/16/2005 – (12/27/2022)
Source: International Carbon Action Partnership (icap), EUA spot price data retrieved from the EEX group, Californian Cap and Trade auction prices retrieved from the Californian Air Resources Board

The price development of allowances of the EU-ETS is shown in Figure 5 and compared with the only existing cap and trade programme of the USA in California. With the introduction of the EU-ETS in 2005, the initial price was just under 5€ but rose to 20-30€ quickly. Hintermann (2010) posits that the release of 2005 emission data, which revealed the over-allocation of the market, caused a significant price crash. However, the market recuperated slightly and sustained a value of approximately €15 for several months before commencing a gradual downturn. By the end of Phase I, EUA prices were almost free of charge. With the start of Phase II in 2008, allowance prices rose to 20-30€ but fell steadily throughout Phases II and III until they stabilised at around 5€ for several years. It was only in 2018 that the price rose again for the first time and, after a volatile phase with minor dips, settled again between €20 and €30. This development is due to the announced plans of the EU to reduce the surplus permits on the market (Twidale et al., 2023).

With the onset of the COVID-19 pandemic, one can see a slump in allowance prices attributed to the decline in economic activity. After the recovery of the economy in the following months and the accompanying increase in prices, the most substantial increase in CO_2 prices comes in 2021 with the start of Phase IV (2021-2030). With the announcement of the European Commission's *Fit for 55* package to reduce EU emissions by -55% by 2030, including carbon-intensive industries such as aviation, prices rose rapidly by 150%. In February 2022, with the start of Russia's war on Ukraine, the CO_2 price cracked the €100 mark and has since experienced its most volatile phase. This increase is due, among other things, to the higher demand for allowances by energy producers, who now have to resort to CO_2-intensive coal as a substitute for Russian gas.

1.4.1 Correlation between Energy and Carbon Prices

The literature on the exact causes of the current skyrocketing prices of EUAs is limited. However, there is literature on the most important price fundamentals. The main drivers of allowance prices are energy prices, institutional decisions, and weather conditions. The role of gas-to-coal fuel switching has already been explained above. The price of EU-ETS allowances has often been discussed in the literature, particularly away from its relationship to energy prices of oil, gas, electricity, and coal. Alberola et al. (2008) examine the three crucial price fundamentals and structural breaks for EU-ETS prices during the first phase from 2005-2007. Their results show that energy sources are statistically significant for determining EUA prices and that price volatilities are effectively transmitted to allowance prices. Aatola et al. (2013) examine the price determination of EU-ETS allowances on different fundamentals in the first and second phases of regulation. The authors' results show a causal and significant relationship between EEA prices and market fundamentals, such as German electricity prices and coal and gas prices. The empirical results obtained from OLS, IV, and VAR models indicate that a substantial proportion, approximately 40%, of the fluctuations in EUA forward price can be attributed to the underlying fundamental factors (Aatola et al., 2013). Batten et al. (2021) use different regression methods to examine the impact of energy prices on EUA prices. The results show that oil, coal and electricity prices and clean dark spread significantly affect the development of EUA prices. Nonetheless, the explanatory power of the oil, coal, and electricity prices, as well as the clean spark spread, was limited to only 11% of the observed variability in the carbon price. (Batten et al., 2021). The authors expect other price fundamentals, like economic activity, policy uncertainty and weather conditions to contribute to the EUA price development.

The literature results are consistent with the price developments of oil and gas described in 1.1 and the developments of EUA prices above. The substantial increases in the last of the allowance prices between 2020 and 2022 (see Figure 5) correlate with the increase in energy prices. However, energy prices only partly explain the increase, as already noted by Batten et al. (2021). Furthermore, the impact of energy fundamentals depends on the period under investigation and the influence of certain institutional decisions, which will be examined in the next section.

1.4.2 Institutional Decisions and Carbon Prices

The regulating authority of the EU-ETS can always take the opportunity to adapt the instrument to new circumstances. The best examples are the European Green Deal or the EU's decision to introduce the CBAM. The regulated sectors and companies are purely reactive in this respect and must adapt to new circumstances. The intuitive idea is that this uncertainty, combined with sudden changes, leads to price spikes of freely tradable allowances. The influence of regulatory decisions and their announcements on EUA prices has yet to be extensively studied in the literature. Nevertheless, some of the few studies will be examined in more detail below.

Mansanet-Bataller and Pardo (2009) analyse the impact of 70 regulatory announcements in the first phase of the EU-ETS on carbon prices and their volatility. Among other things, the authors analyse the first price drop of the first phase in 2006, which lasted until the end of the pilot period. The results of the study show that regulatory announcements (both positive and negative) have an impact on EUA prices. This effect could be seen mainly on the announcement day, in some cases a few days after the announcement and surprisingly also a few days before the announcement (Mansanet-Bataller & Pardo, 2009). Mansanet-Bataller and Pardo (2009) interpret this result as indicating that knowledge leaks existed before the announcement. Unlike energy prices (see 2.2.1), no effect on changes in price volatility was found. Conrad et al. (2012) analyse how the prices of EU-ETS allowances react to announcements of the European Commission on regulations, macroeconomic development forecasts and actual economic activity. The authors found a significant and immediate increase in EUA prices for all three.

The literature on the influence of institutional decisions and announcements is not yet pervasive. Nevertheless, the factor should be addressed as a price driver. It is expected that the EU (especially regarding the reduction of emission allowances) will still undertake some regulatory changes and announcements. Whether and to what extent these will influence prices remains speculative and offers material for future studies.

1.4.3 Carbon Prices and Extreme Weather Events

Another factor identified in the literature as driving prices is the weather situation. Especially hot or cold, dry, or wet periods can influence the price of EUAs. The intuitive idea is that certain temperatures or weather conditions influence energy consumption. An example of the impact of seasonal weather variations on energy demand is the increase in heating requirements during cold winters, which results in a corresponding increase in power generation needs or, similarly, hot summers, which create a greater demand for air conditioning, leading to a rise in electricity production (Chevallier, 2012, p. 41). Since more fossil fuels are needed for energy production (except for renewables), more CO_2 allowances are needed. Higher demand with constant supply leads to scarcity and, thus, higher prices. The extent of this effect has been investigated in several studies, some of which will now be examined in more detail.

Mansanet-Bataller (2006) examine the impact of weather and energy variables on the price determination in the EU-ETS. While the authors conclude that very cold or very hot weather can influence the price of EUAs, energy variables such as coal and oil have a much more significant impact on prices (Mansanet-Bataller et al., 2007). The research provided by Alberola et al. (2008) supports this previous literature on the influence of weather on EUA prices. However, the authors particularly emphasise that it is not especially hot temperatures that contribute to rising prices, but rather unanticipated extreme weather events that trigger these developments (Alberola et al., 2008, p. 795). Christiansen et al. (2005) mention the double effect of weather on emission production and hence the demand for CO_2 allowances. On the one hand, the authors describe the effect mentioned above, and on the other hand, they also consider the effect that, e.g., rainfalls and wind speed have on countries that rely on hydro- or/and wind power. For Instance, Christiansen et al. (2005) mention how Norway had to import more coal-generated power from Denmark due to dry years between 1996 and 1999. The energy exports in Denmark increased, and the total emissions did as well. Suppose such events occur under the EU-ETS regulation. In that case, this means that the power plant operators will demand a significantly higher quantity of certificates, and thus the price will also increase.

The authors' research has important implications for the future price development of EUAs. According to the European Environment Agency, temperatures and extreme weather events have increased significantly in the EU (European Environment Agency, 2022b). While forest fires and droughts are most common in the south, floods are most common in central Europe. The increase in (unexpected) extreme weather should also be addressed as a significant driver of certificate prices.

2 The Effect of Carbon Pricing under the EU-ETS on Companies

The first chapter illustrated the price development of the fossil fuels oil and gas and made an important link to energy production and fuel use. The high prices for natural gas have caused energy producers to switch from gas-fired power plants to higher utilisation of existing coal-fired power plants. This gas-to-coal fuel switch has important implications for the EU's CO_2 emissions, as coal emits significantly more climate-damaging carbon than natural gas. The analysis of the price development of EUAs underlines this finding, as the higher demand of energy producers for allowances to compensate for the new emissions led to a price surge in the EUA market. In addition to energy prices, other price fundamentals, such as institutional decisions and announcements and extreme weather conditions, were also examined. These fundamentals play an important role in the future institutional design of the EU-ETS.

This chapter will examine the consequences of high allowance prices for companies. In this context, the effects on the competitiveness of regulated European companies, the phenomenon of carbon leakage and the consequences for corporate investments are particularly relevant. Sections 2.1 and 2.2, *ex-ante* and *ex-post* studies on the effects of carbon pricing on the distortion of competition and carbon leakage, are used and critically reviewed. It is found that only a few conclusions can be drawn about the current effects, in particular, due to the previous low level of pricing. The impact of carbon pricing on corporate investment behaviour, discussed in section 2.3, provides interesting insights into the consequences of the EU cap-and-trade system, and provides arguments for potential adjustments to the regulatory framework, which form the core of this thesis (see Chapter 3).

2.1 The Pollution Haven Effect and the Porter Hypothesis

Two concepts are fundamental when discussing these corporate effects: the Pollution Haven and the Porter hypotheses. „The pollution haven hypothesis […] predicts that more stringent environmental policies will increase compliance costs and, over time, shift pollution-intensive production toward low abatement cost regions, creating pollution havens and causing policy-induced pollution leakage" (Dechezleprêtre & Sato, 2017, p. 183). Environmental regulation thus causes a migration of both economic power and emissions (to be controlled) abroad. A special form of this effect is the so-called *carbon* *leakage*. In contrast, Porter and van der Linde (1995) posit that strict regulatory environmental standards can enhance a corporation's competitiveness by incentivising cost-saving optimisations that mitigate regulatory expenses and by encouraging technological advancements that translate to a competitive advantage in the global market. This effect is referred to in the literature as the so-called Porter hypothesis.

2.2 Deteriorated Competitiveness under the EU-ETS

A broad range of literature investigated the effects of the EU-ETS on the competitiveness of European Industry and examined whether or not it affects firm profitability. A remarkable amount of literature has emerged around the assumption that environmental regulation has no or only a minimal negative effect on the competitiveness of companies and that there is no significant empirical evidence for the Pollution Haven Hypothesis induced by stringent EU-ETS regulations. These studies are overshadowed by, on the one hand, the difficulty of empirically proving the pollution haven effect and, on the other hand, the fact that all the studies examined concentrate on the first two phases of the EU-ETS, in which the majority of the licences were freely allocated and thus did not cause any significant cost effect.

The impact of environmental regulation on the private sector has also been researched independently of the EU-ETS, and many authors confirm that there are indeed adverse effects on businesses from the introduction of strict environmental regulations. An example of this *ex-ante* research, Greenstone et al. (2012) use a sample of 1.2 million manufacturing plants and data from the Annual Survey of Manufacturers to calculate the effect of introducing strict air quality regulation in the US on total factor productivity (TFP). The authors calculate that in the selected sample, introducing an environmental regulation reduced the TFP of companies by about 2.6% on average. Gray & Shadbegian (2001) use sample data from 116 pulp & paper mills to determine the impact of environmental regulation on this specific industry. They argue that the calculations should consider the differences between plant-based technologies. Pulp & Paper Mills have to incur higher emission abatement costs due to the introduction of environmental regulations, reducing productivity. Within a technological interaction model, it was estimated that the aggregate expenses of pollution abatement harmed productivity, leading to a mean reduction of 4.6% across all industrial facilities. (Gray & Shadbegian, 2001).

While these authors found evidence that stringent environmental regulations negatively impact manufacturing productivity, the econometric literature on the EU-ETS does not find evidence that the regulatory requirements for the European manufacturing industry produce harmful effects. Using data on 5,873 firms in a sample of ten European countries from 2001-2009, Chan et al. (2012) assess the impact of the EU-ETS on three variables used as a proxy for firm competitiveness – unit material costs, employment, and revenue. They compare the competitiveness in regulated and non-regulated scenarios for the three most emission-intensive industrial sectors, namely the energy, cement, iron, and steel industry. The results of their analysis indicated a statistically significant impact on material costs and turnover in power plants, but no such effects were observed on the three variables of interest in cement, iron, and steel companies (Chan et al., 2012). Petrick and Wagner (2014) tackle the matter of competitiveness by assessing the causal impact of the EU-ETS on the employment rate, gross output, and exports of firms taking part in the system for a sample of regulated German manufacturers. Although they find significant reductions in emissions, these reductions cannot be traced back to decreases in productivity. Based on their estimates, the hypothesis that the EU-ETS reduces gross output or exports can be rejected, and the employment effects are statistically and economically insignificant (Petrick & Wagner, 2014). Wagner et al. (2014) conducted longitudinal research, analysing the impact of the EU-ETS on firm competitiveness in France using plant-level data from 4,500 French manufacturing companies. The regulated companies were able to reduce their emissions on average by 20% compared to non-regulated firms. However, Wagner et al. (2014) also find statistically significant reductions in the employment of about 7% compared to non-regulated firms (Wagner et al., 2014).

Joltreau & Sommerfeld (2019) investigated why the existing literature on the EU-ETS could not find any or only minor adverse effects on competitiveness. Firstly, the literature mainly studied Phases I and II of the EU-ETS, where allowances were freely distributed, which did not result in a significant cost impact for companies. Since in Phase III, the allocation method for carbon allowances was introduced and free allocated certificates were reduced to 30% in 2020 (European Court of Auditors, 2020), the purchase of emission allowances may result in short-term negative competition effects due to the added costs involved (Joltreau & Sommerfeld, 2019, p. 457). Secondly, Joltreau & Sommerfeld (2019) documented an over-allocation of carbon allowances in Phase I and II, indicating that most companies held more allowances than needed and could generate revenue from selling them. Industrial operators that are short in allowances profit from the low carbon prices resulting from oversupply. Joltreau & Sommerfeld (2019) name the possibility of passing through costs to consumers as a third hypothesis for why the EU-ETS did not deteriorate competitiveness. While the energy sector can pass through most of its carbon costs, this accounts only for some manufacturing operators.

Section 1.4 analysed the past development of the EUA price and looked at the most important drivers and price fundamentals. It is important to remember that the literature on competitiveness under the EU-ETS focuses mainly on Phases I-III, where many allowances were freely allocated, and prices were too low to trigger a significant cost effect. With Phase IV and the price increases seen so far, the question of competitiveness may arise again. Low carbon pricing can diminish the motivating forces for prompt investment in low-carbon technological advancements and may impact the dynamic efficiency of the system. Consequently, the negative impacts on competitiveness may manifest themselves, particularly when more demanding abatement measures become necessary (Joltreau & Sommerfeld, 2019).

2.3 Pollution Haven Effect and Carbon Leakage

The literature on the deterioration of competitiveness has shown that the EU-ETS has had no impact on proxy variables such as profitability, employment, or exports. It has also been explained that these effects may occur later under the stricter Phase IV requirements and the price drivers explained in 1.5. The question now arises whether, despite the lack of adverse effects of the EU-ETS, the so-called pollution haven effect has nevertheless occurred, i.e. whether (emission-intensive) companies have decided to relocate their production to less strictly regulated countries abroad under the EU-ETS regulation. In connection with this, a particular form of PHE will be examined: carbon leakage. Carbon Leakage describes the same phenomenon as the pollution haven effect, so the relocation of emission-intensive activities to non-EU countries with less ambitious emission regulations to avoid costs for carbon allowances, however, also assumes that significantly more is emitted abroad and that global emissions of greenhouse gases increase instead of decreasing (European Commission, 2022).

Carbon leakage has yet to be studied extensively in the literature to date. The lack of empirical evidence could be assigned to the difficulties in measuring the effect. The examined literature uses different methods to determine whether the European manufacturing sector tends to move abroad in the face of strict environmental regulations. Dechezleprêtre et al. (2021) studied the carbon leakage effect by looking at multinational companies. According to the authors, international companies are particularly vulnerable because they can quickly shift production from highly regulated to less regulated regions. Their research uses data on the geographical distribution of emissions within companies. A total of 1,122 companies were examined. Their research reveals that operating in regions outside the EU, where climate policies are less strict, does not enhance the probability of decreasing the proportion of EU emissions (Dechezleprêtre et al., 2021, p. 27). Thus there is no empirical evidence that the EU-ETS caused carbon leakage in the sample. Martin et al. (2014) use a different method. They conduct interviews with the managers of 761 manufacturing operators from 6 different EU countries, which allows them to determine whether these companies are taking actions such as downsizing or relocating to less regulated countries in light of environmental regulations. Martin et al. (2014) found no evidence that an average firm, independent of its sector, would shut down its operation and move abroad to countries outside the EU. Another method of measuring carbon leakage is via (neo-) classical trade theory. Based on the New trade theory, Naegele and Zaklan (2019) assume that trade flow changes, especially embodied carbon flows, can serve as a measure of leakage. The authors consider the EU-ETS's effect on net and bilateral trade flows. According to the findings of this study, there is no empirical evidence that the EU-ETS has led to carbon leakage within the manufacturing industry.

Sartor (2013) and Branger et al. (2016) use trade theory in a sector-specific context. Sartor (2013) investigates whether the EU-ETS caused carbon leakage in the aluminium sector in the first 6.5 years, i.e. Phases I and II. The author examines changes in net imports of aluminium from 2005-2011. His research shows that the EU-ETS did not cause carbon leakage in the aluminium sector in its initial phase. The sector-specific study by Branger et al. (2016) examines the phenomenon of competition-driven carbon leakage in the cement and steel industry within Phase I and II of the EU-ETS. They apply econometric methods to evaluate the correlation between the carbon price and net imports while controlling for other variables that may influence net imports, including economic activity within and beyond the European region (Branger et al., 2016, p. 110). Their findings suggest that there has been no evidence that the EU-ETS triggered carbon leakage in the cement and steel industry in the first two phases of the EU-ETS.

A frequently cited reason for the absence of carbon leakage in the literature reviewed is that the price signals of the EU-ETS were too low in the first two phases and partly in the third phase. The costs that companies had to bear were too low to trigger the relocation of production. Moreover, the act of relocating carries with it opportunity costs in the domestic market, including a reduced market position and diminished bargaining power with policymakers (Felbermayr & Peterson, 2020).

2.4 The EU-ETS and Firm Investment

There are two main discussions about the influence of environmental regulation on corporate investment decisions. First, there is the question of whether the EU-ETS influences companies' FDI decisions and causes so-called „investment leakage". Intuitively, two hypotheses have to be investigated: firstly, whether lenient policies act as a stimulant for inbound manufacturing investments, and secondly, whether strict policies serve as a catalyst that influences decisions regarding outward investment flows or relocation choices (Dechezleprêtre & Sato, 2017). Second, there is the question of whether regulatory requirements on emission levels encourage companies to invest in new technologies to avoid abatement costs, allowance purchases, or pay penalties. The second discussion revolves around the assumptions of the *Porter Hypothesis* that environmental regulation incentivises companies to invest in new technologies. The literature distinguishes between the *weak* and *strong* versions of the Porter hypothesis. Jaffe & Palmer (1997) were the first to make this distinction. The weak version of Porter's hypothesis „says only that regulation will stimulate certain kinds of innovation", but „since [the] addition of constraints to a maximization problem cannot improve the outcome, the weak version implies that the additional innovation must come at an opportunity cost that exceeds its benefits" (Jaffe & Palmer, 1997, p. 610). In its *strong* version, the Porter Hypothesis states „that regulation induces innovation whose benefits exceed its costs, making the regulation socially desirable, even ignoring the environmental problems it was designed to solve" (Jaffe & Palmer, 1997, p. 611).

In the discussion on investment leakage, i.e. the migration of direct investment abroad, *ex-ante* studies such as that by Böhringer et al. (2012) find indications of leakage risk. The authors use a multi-regional, multi-sectoral computable general equilibrium (CGE) model and find 5-19% investment leakage rates in the reference scenario (Böhringer et al., 2012). From a sectoral *ex-ante* perspective, Kuik (2014) uses a recursive-dynamic multi-sectoral, multi-regional equilibrium (CGE) model of how different international climate policy scenarios affect European steel industry capital flows. According to Kuik (2014), in the year 2050, approximately 60% of carbon leakage is expected to be attributed to *investment leakage* (Kuik, 2014).

The *ex-post* research on investment leakage concludes that investment leakage abroad has yet to occur under the EU-ETS. Borghesi et al. (2020) use a panel data set covering 22,000 companies from the Italian manufacturing sector to analyse the impact of the EU-ETS on FDI decisions. Their findings suggest that the EU-ETS had a limited impact on the extensive margin, i.e., the number of subsidiaries of the firms, while exhibiting a notable effect on the intensive margin, i.e., the sales of the subsidiaries. This suggests that the companies may have preferred to augment production within their overseas subsidiaries instead of establishing new subsidiaries. Koch and Basse Mama (2016) examine the impact of the EU-ETS on outbound FDI decisions in German international firms. The firms that relocated were not found to be active in the energy-intensive sectors targeted by the policy, nor were they characterised as having high emission intensities. Rather, these firms were identified as possessing a scarcity of permits and were engaged in operating combustion plants within sectors - particularly machinery - that typically exhibit greater geographical mobility, owing to relatively low fixed costs (Koch & Basse Mama, 2016, p. 27).

The *ex-post* investigations have shown no significant investment leakage effect for European industrial companies in the previous phases of the EU-ETS. The question now is whether the companies then made their investments in the geographical area of the EU-ETS, e.g. in the form of new production technologies to save emissions and thus regulatory costs (the weak version of PH) or in the form of new production facilities with output growth (the strong version of PH). Is the regulatory framework of the EU-ETS well-designed enough to trigger investments in a way that even stimulates productivity in European industry?

Rubashkina et al. (2015) examine the manufacturing sector of 17 different European countries to test the validity of the Porter hypothesis in both its weak and strong versions. Their research supports the weak version of the Porter hypothesis, i.e., there was no reduction in the level of innovation with stricter requirements, proxied by pollution abatement costs and expenditures (PACE). Nevertheless, this effect was visible only on patent applications but not total R&D expenditures. Rubashkina et al. (2015) fail to find evidence favouring the strong version of the Porter hypothesis. Lundgren et al. (2015) conducted research to examine the influence of carbon and energy taxes implemented in Sweden and the EU-ETS on the operational efficiency of Swedish pulp and paper firms from 1998-2008. They examine whether the market-based prices stimulated technological development in this industry. Lundgren et al. (2015) observe that despite an increase in firms' productivity over the study period, the growth in productivity was predominantly attributed to non-market-based factors rather than economic or environmental policy instruments. Furthermore, the authors note that no significant technological developments have occurred, as prices were too low during the period studied to provide incentives for innovation. These findings are consistent with Brohé and Burniaux's (2015) research, which also sees the too-low prices as the cause of a lack of innovation. The authors conducted interviews with 64 managers from Belgian industrial sites. Overall, the market prices of allowances were perceived by operators as too low to incentivise investments in new technologies.

Lazzini et al. (2021) contribute the latest findings to the study, including the beginning of the third phase in their research and Phases I and II of the EU-ETS. In line with Lundgren et al. (2015) and Brohé and Burniaux (2015), they write that the oversupply of allowances and low prices did not create incentives to invest in reducing emissions. During Phase III, the provision of free allocation below the verified emissions level tends to create managerial incentives for technology investments to reduce emissions (Lazzini et al., 2021, p. 2348). The findings of Lazzini et al. (2021) serve to complement the work of Rubashkina et al. (2015), as they corroborate the notion that the earlier regulatory framework within the EU-ETS has effectively enabled businesses to make strategic decisions that have resulted in heightened environmental efficiency and sustained economic performance (Lazzini et al., 2021, p. 2348). However, in contrast to the principles of the Porter hypothesis, the results of Lazzini et al. (2021) do not provide any conclusive indications of an improvement in economic performance that can be attributed to the EU-ETS regulation. The EU-ETS was thus able to support the weak version of the Porter hypothesis, as companies made investments to offset costs and secure economic performance. However, regulation has not yet achieved investments that have increased performance and given regulated industries a competitive advantage, i.e. there has been no expression of the strong version of the Porter hypothesis.

Dechezleprêtre and Sato (2017) conclude that environmental regulations can only accelerate economic growth if they lead to a steady rate of innovation. Instead, it seems „that regulation-induced environmental innovations tend to replace other innovations, leaving the overall level of innovation unchanged” (Dechezleprêtre & Sato, 2017, p. 199).

2.5 Interim Conclusion

Chapter One analysed the first hypothesis of whether the rising energy prices between 2021-23 gave rise to the surge in EUA prices by reviewing the research of several authors. The research found that the demand for coal increased during the energy crisis, resulting in a switch from gas to coal for power generation in Europe. This shift to coal led to a higher amount of emissions and an increase in the demand for EU-ETS emission allowances. However, the literature review on the fundamental price drivers of EUA prices showed that energy prices alone were not the only driving force of EUA price changes. Factors such as regulatory announcements and extreme weather events also played a significant role, declaring the first hypothesis false.

Chapter Two examined the hypothesis that carbon pricing under the EU-ETS negatively affects regulated companies. Three aspects, including the deterioration of competition, carbon leakage, and investment decisions, were examined through an extensive literature review. Contrary to *ex-ante* studies' predictions, *ex-post* studies could not find empirical evidence for the distortion of the companies’ competitiveness and the phenomenon of carbon leakage. While no negative effects were determined for Phases I to III, the conclusions about the current phase are distorted as the low prices during the studies limit the extent to which possible conclusions could be drawn. Hence, the assumption of the second hypothesis cannot be falsified nor confirmed.

What conclusions can be drawn from the results so far? First, the first chapter has shown that price changes cannot be attributed exclusively to exogenous shocks. This has important implications for the design of the instrument. If it had turned out that EUA prices were mainly due to energy prices, a short-term adjustment of the EU-ETS would be necessary. But since the EUA price increases are only partly - according to Aatola et al. (2013), just under 40% - due to energy prices and institutional decisions being considered the main price drivers, an instrument is needed that can set incentives for improvement in the long term. But is there even a need to adapt the current cap-and-trade system? After all, the literature study has shown that companies have felt no negative effects so far. However, the research has also shown that while investments under the EU-ETS contribute to emission control, these investments often replace originally planned investments in, for example, productivity-enhancing technologies (Dechezleprêtre and Sato, 2017). In the terminology of Porter's hypothesis, the EU-ETS promotes the shift towards a more sustainable economy but has so far not positively impacted firms' productivity. Optimally, productivity should not suffer under environmental regulation. At the same time, the EU is aiming for ever more ambitious climate policies. With the enactment of the Fit-for-55 Package, the cap of the EU-ETS is now being reduced even faster, and the regulation covers additional sectors such as shipping and transport (Council of the European Union & European Council, 2023). At the same time, forecasts do not see the EUA price falling in the future. Instead, the average price is expected to stabilise at €85.45 between 2022-25 and increase to an average of €99.63 between 2026 and 2030 (IETA, 2022). The EU's CBAM aims to discourage companies from moving abroad (i.e. prevent carbon leakage) by making imported goods more expensive. However, it does not solve the problem that companies lack incentives to invest in productivity beyond emission-saving technologies.

The proposal in the next chapter is an alternative to the EU's current approach. Instead of making carbon increasingly expensive and thus increasingly burdensome for companies, the model incentivises companies to abate emissions beyond the efficient emissions level.

3 An Adaptation to the EU-ETS

The following chapter presents an adaptation for the EU-ETS, which is intended to set new incentives for companies to invest actively, considering the challenges of the current energy crisis. Employing a market-based subsidy, companies with voluntary abatement above the efficient emission level should be rewarded and reduce their costs for innovative optimisations. The basis for the incentive-based instrument is the model developed by Evan Kwerel (1977), who used this model to address the problem of imperfect information in companies' transfer of emission abatement costs. Based on a marginal cost theory, the model is considered in a new problem context in this paper and supplemented by extensive framework extensions.

3.1 A Marginal Cost Perspective to the Determination of Emission Levels

The basis for a model of an incentive-based subsidy solution is a marginal cost approach to environmental damage and emission abatement costs. This model is widely used in environmental economics and is described in Perman et al. (2003). This marginal cost approach is used to determine the most cost-effective and, thus, economically efficient level of emission levels. This section overviews the underlying assumptions, cost functions, and properties.

Figure 4 shows the model that forms the basis of the incentive-based subsidy. In this marginal cost approach, two curves are described that are associated with the following assumptions. First, it is assumed that each unit of emissions emitted (measured in CO_2eq) causes environmental damage. Perman et al. (2003) describe different methods to measure the value of environmental damage. For this paper, it is assumed that the environmental damage is known to the regulating authority and that it can quantify it accurately. The environmental damage is approximately described by the function $D(m)$, where m represents the number of emissions emitted. The derivative of this function, $D'(m)$, describes the marginal cost of environmental damage, i.e. the damage to the environment caused by an additional unit of emissions, expressed in monetary units. It holds that $D'(m) > 0$ and $D''(m) \geq 0$. The marginal environmental damage is calculated in monetary units. The second assumption is that a company j bears costs to reduce or abate emissions. These emission abatement costs are described by the function $C_j(m)$. It is assumed that the regulating authority (EU) can approximate the aggregate abatement cost function based on the previous EUA auctions. It holds for the marginal abatement costs that $C_j'(m) < 0$ and $C_j''(m) \geq 0$. The aggregate emission abatement function includes the costs of all firms within the regulated region.

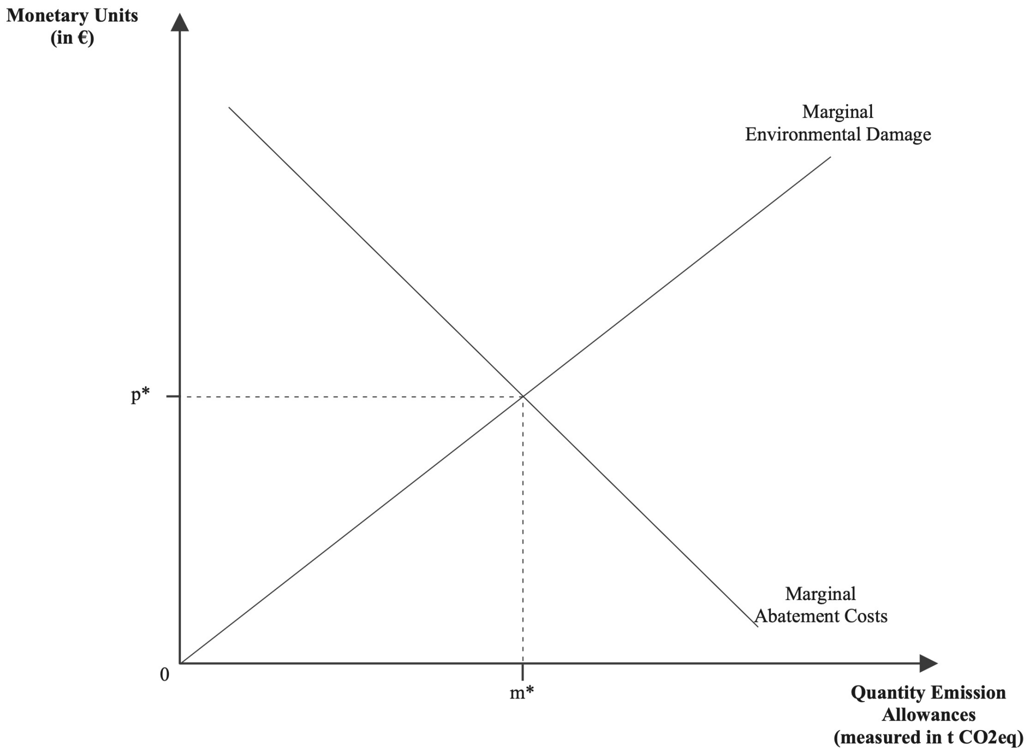

Figure 4: Efficient Level of Emissions under perfect Information

The attributes assigned to the functions described above also refer to the curvature behaviour of the cost or damage functions, i.e. their convexity and non-concavity. Perman et al. (2003) discuss the convexity of the environmental damage and abatement cost functions. Perman et al. (2003) write that for marginal environmental damage, environmental economists generally assume that total damage increases at higher emission levels with increasing rates, i.e., the environmental damage function exhibits a leftward curvature or convexity. The situation is similar for the marginal abatement costs of companies. Here, the costs potentially increase with higher avoidance, i.e. the total abatement costs also exhibit convexity. Perman et al. (2003), however, also go into the discussion on non-convexity and looks here, above all, at the much-discussed question of convexity in environmental damage functions. Perman et al. (2003) mention the so-called threshold effect above all. Assume that corrosive substances flow into a pond, harming the flora and fauna. Above a certain acid level, all living organisms and plants will already have died out, so continuous pollution with corrosive substances can no longer cause further damage. In this case, we would speak of a non-convex damage function resulting from a saturation effect. However, it is also important to note that these terminological twists only play a role in discussing the functions to the extent that they enable the determination of efficient emission levels in the model (Perman et al., 2010, p. 187). This is the case for both convex and non-convex functions. To simplify the graphical representation, linear non-convex marginal costs are presented in this chapter. However, the market-based function proposed later is based on assumptions that allow the convexity

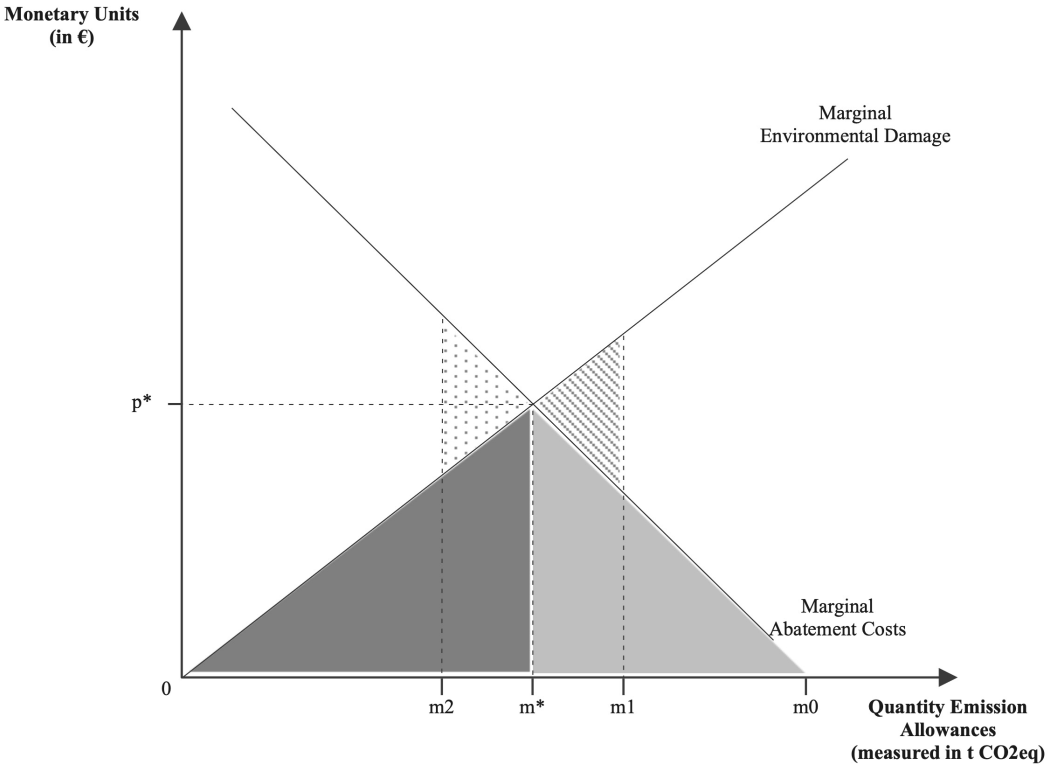

Figure 5: Deadweight losses under inefficient emission levels

of the functions as well.

The efficient emission level lies at the intersection of the marginal environmental damage function and the marginal aggregate removal function, i.e. $D'(m) + C'(m) = 0$. This intersection is the most cost-effective emission level, as the damage caused by emissions and the costs for emission abatement, measured in monetary units, are equal here – a shift of the emission quantity away from the set efficiency level results in a deadweight loss. The cost efficiency at emission level m^* can be explained in more detail by looking at Figure 5. If exactly the efficient emission level m^* is emitted, the amount of the total cost is the environmental damage $MD(m^*)$ (coloured dark grey) and the costs incurred for emission abatement $MAC(m^*)$ (coloured light grey). For an emission level m_1, for which it holds that $m_1 > m^*$, not enough emissions are removed by the companies, and the total costs are the costs mentioned above plus the grey-shaded area that expresses the additional environmental damage incurred at the emission level m_1. If the actual emission level is $m_2 < m^*$, companies have to incur higher costs to reach the set emission level, which exceeds the benefit of the saved environmental damage. Additional costs in the amount of the grey dotted area below the marginal abatement cost function occur in this scenario. The market-based subsidy addresses the second case.

If the regulating authority sets the efficient emission level to m^*, compliance costs are incurred by the companies. These costs $C_j(m^*)$ consist of the costs that a company j has to spend to purchase emission allowances at the efficient level m^* and the removal costs up to the efficient level m^*. The cost of buying emission allowances $C_{EUA}(m^*)$ can be described by

$$C_{EUA}(m^*) = p^*m^*$$

In a scenario with no environmental regulation, a firm j decides to emit the maximum amount of emissions and does not undertake any abatement activities. m_0 denotes this state in the model. Thus, if the regulating authority determines the efficient pollution level m^*, companies have to incur costs to reduce emissions from level m_0 to level m^*. These abatement costs $C_{Ab}(m^*)$ can be described by

$$C_{Ab}(m^*) = \int_{m*}^{m0} MAC$$

For the efficient emission level m^*, there are, therefore, total costs amounting to

$$C(m^*) = C_{EUA}(m^*) + C_{Ab}(m^*)$$

or

$$C(m^*) = p^*m^* + \int_{m*}^{m0} MAC$$

As explained in 2.1.3, EU companies submit their bids, including the amount of EUAs and the price bid to the auction platform EEX. Subsequently, the auction platform arranges the bids in a descending sequence, which can be construed as a demand curve for EUAs. „Assuming that no strategic behaviour takes place in the bidding process, this demand curve will be identical to the aggregate marginal abatement cost function" (Perman et al., 2010, p. 225). Assuming that the regulating authority has all the above information and thus knows the efficient emission level, Figure 6 describes the mechanism of auctioning emission allowances. The EU-ETS is a quantity-based instrument. The EU sets the level m*, and the equilibrium price *p** results from the EEX auctions.

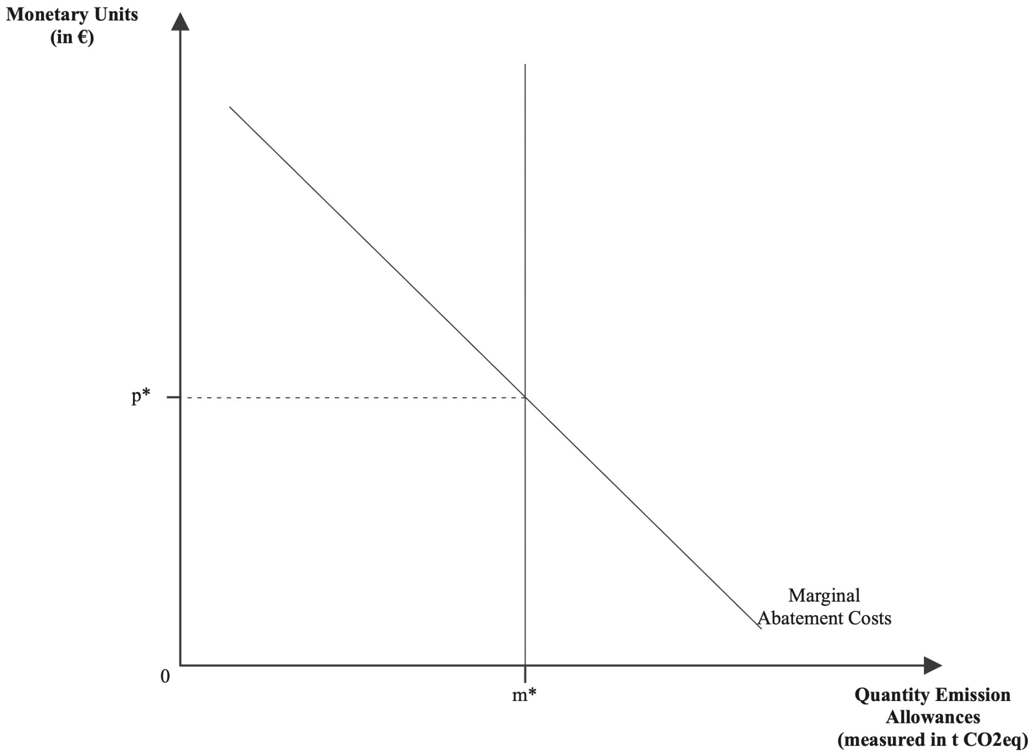

Figure 6: The Auction mechanism in the EU-ETS under perfect information

3.2 The Market-Based Subsidy for Excess Emission Abatement

This chapter hypothesises that introducing a market-based subsidy as a complement to the existing regulatory framework will incentivise industrial firms to increase investment and innovation. The goal should be to create a regulatory framework under which the strong version of Porter's hypothesis is supported, i.e. that the „regulation induces innovation whose benefits exceed its costs, making the regulation socially desirable, even ignoring the environmental problems it was designed to solve" (Jaffe & Palmer, 1997, p. 611). For this state of affairs to occur, an environment must be created in which companies innovate to improve their environmental performance (i.e. emissions-reducing innovations) and improve productivity and competitiveness in the global market. To this end, the introduction of a market-based subsidy is proposed below.

The section above explains that moving away from the efficient emission level m* leads to a deadweight loss. In the following, an instrument (a market-based subsidy) is designed that proposes to move away from this efficient emission level. However, why do this when the efficient emission level offers the most cost-effective solution? The proposed instrument provides an alternative to the scarcity policy mentioned in Chapter One, which causes the prices of EUAs to skyrocket. So instead of overburdening companies, the new instrument aims to incentivise them to save emissions beyond the efficient emissions level without incurring additional costs. The subsidy compensates for the deadweight loss mentioned above. This can generate a higher social benefit, as pollution is reduced without imposing an additional burden on companies (see section 3.2.4). As the subsidy can be financed through existing financial resources (see section 3.2.5), there is also no additional burden on the European subsidy. Under the market-based subsidy, the original efficient emission level m* becomes a Pareto-inferior state. At least that is the theory, but what does it look like in practice?

3.2.1 Assumptions of the Market-Based Subsidy

The following assumptions are made for the market-based subsidy model. Firstly, the emission allowances are allocated with an auction mechanism described above. It is assumed that the auction participants, i.e. the European industrial companies, do not pursue any strategic behaviour. Secondly, it is assumed that a company has acquired and precisely holds the quantity m^* of emission allowances. Thirdly, a subsidy is introduced that is paid out for each unit of emissions saved above the efficiency level m^*. The market price p^* of emission allowances determines the amount of the subsidy s, i.e. $s = p^*$. Fourthly, companies are assumed to calculate their emission abatement costs by employing so-called engineering models. These engineering models, or *bottom-up* approaches, set a specific emissions target. They then list all the techniques and technologies that can contribute to achieving this target within a company. „For each technique, the researcher calculates the expected expenditures by firms on pollution abatement equipment and other investments, fuel, operation, maintenance and other labour costs" (Perman et al., 2010, p. 189). It is assumed that companies know these costs and based on them, submit their bids for emission allowances, which serve as information for the regulatory authority to determine the efficient emission level. The model is shown in Figure 7.

Figure 8 shows the case where emissions are saved above the efficient emission level *m**. The scenario shows a company *j* that has reduced the emitted CO_2eq to level *m'* through investments and innovations.

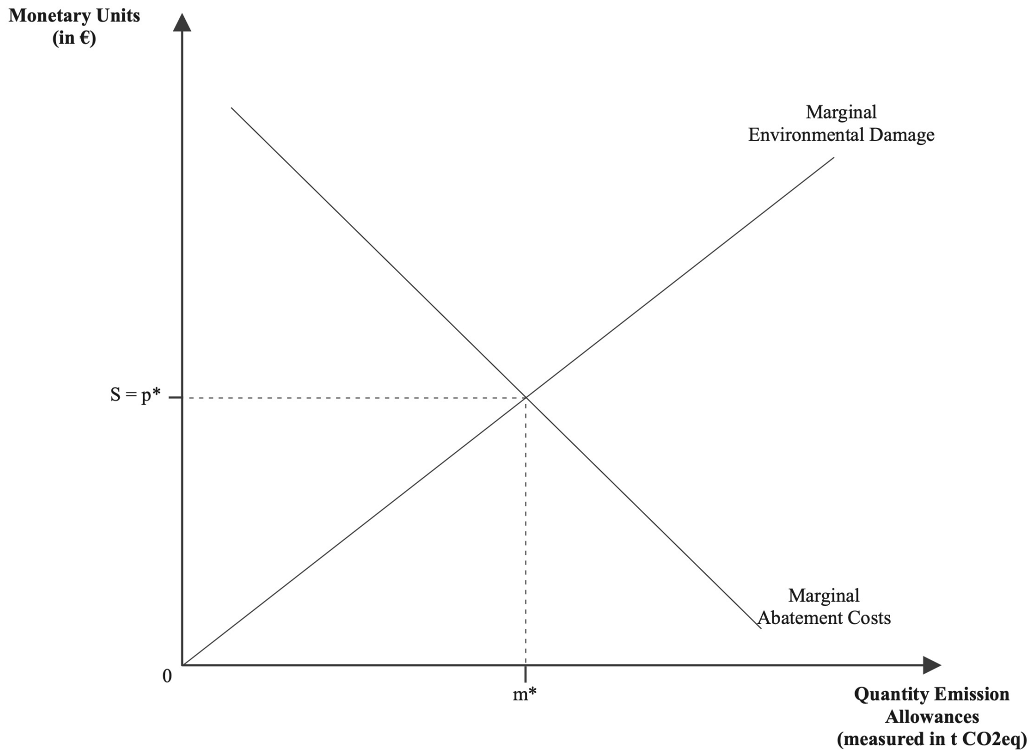

Figure 7: The marginal cost perspective with a market based subsidy

In this scenario, company *j* qualifies to receive the subsidy of $s = p*$. Furthermore, the emission allowances are tradable. The company is assumed to sell its allowances if the emission level *m'* is below m*, i.e. $m' < m*$. The company sells its surplus allowances for the market price *p**. Under this framework, excess emissions abatement by company *j* results in an additional benefit $AB_j(m')$ from the sale of surplus allowances $p*(m*-m')$ and the receipt of the subsidy $s(m*-m')$. It holds:

$$AB_j(m') = p*(m*-m') + s(m*-m')$$

Adding $s = p*$ we obtain:

$$AB_j(m') = 2p*(m*-m')$$

If duplicated, the shaded area in Figure 8 represents the additional benefit of an excess reduction in emissions.

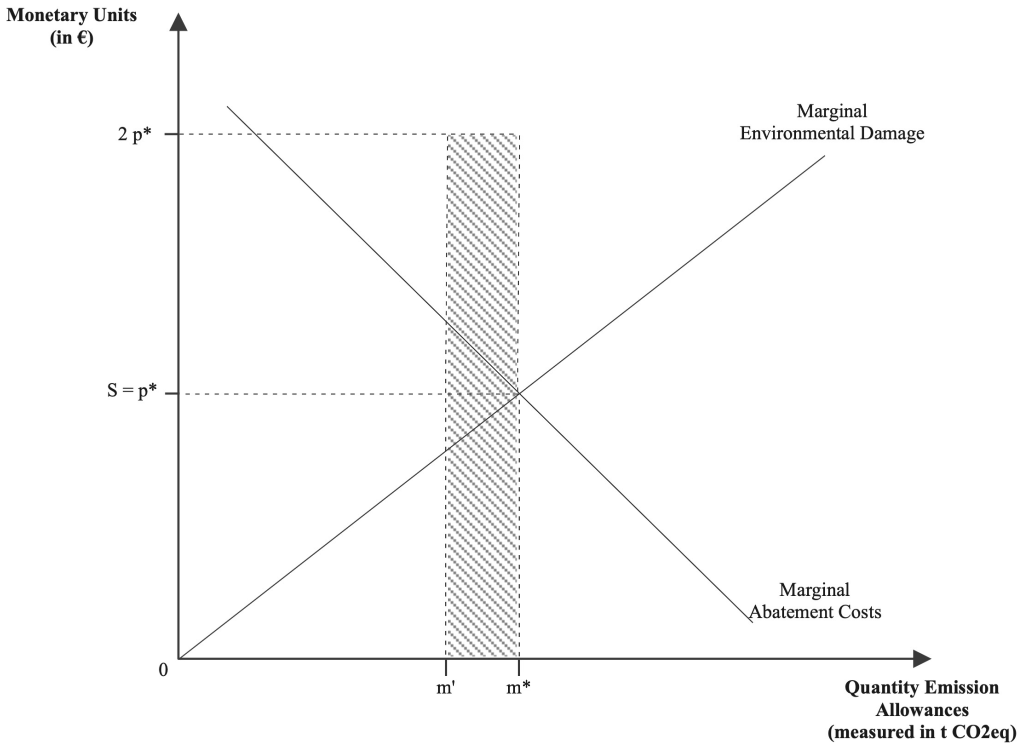

Figure 8: Additional benefits for companies under the excess emission abatement scenario

3.2.2 Effect of a Market-Based Subsidy on the Company Net Costs

The market-absorbed subsidy introduced above aims to set incentives in the EU-ETS so that companies voluntarily make investments that bring the emission level below the efficient emission level in the conventional model. In short, environmental regulation should be designed so that the overall welfare of society increases, i.e. the total benefits outweigh the costs of regulation, while the environmental damage also decreases. The additional benefit $AB_j(m')$ for an emission saving m' has been explained. Nevertheless, the net benefit must be calculated for a detailed diagnosis.

Figure 9 shows the model in a net benefit analysis. At an emission level m', a company j incurs additional abatement costs, which are coloured grey in the figure. These additional costs $AC_j(m')$ can be described by

$$AC_j(m') = \int_{m'}^{m*} MAC$$

and are shaded grey in Figure 9.

The additional benefits $AB_j(m')$, as well as the additional costs of excess emissions $AC_j(m')$ under a market-based subsidy, are added to the costs $C_j(m^*)$ of the EU-ETS at the efficient emissions level m*. With the addition of these costs, a net cost function $NC_j(m')$ can be constructed, which describes the total costs for companies of reducing emissions to level m'. This net cost function is composed as follows:

$$NC_j(m') = C_j(m^*) - AB_j(m') + AC_j(m')$$

$$NC_j(m') = p^*m^* + \int_{m^*}^{m0} MAC - 2p^*(m^*-m') + \int_{m'}^{m^*} MAC$$

$$NC_j(m') = p^*m^* + \int_{m'}^{m0} MAC - 2p^*(m^*-m')$$

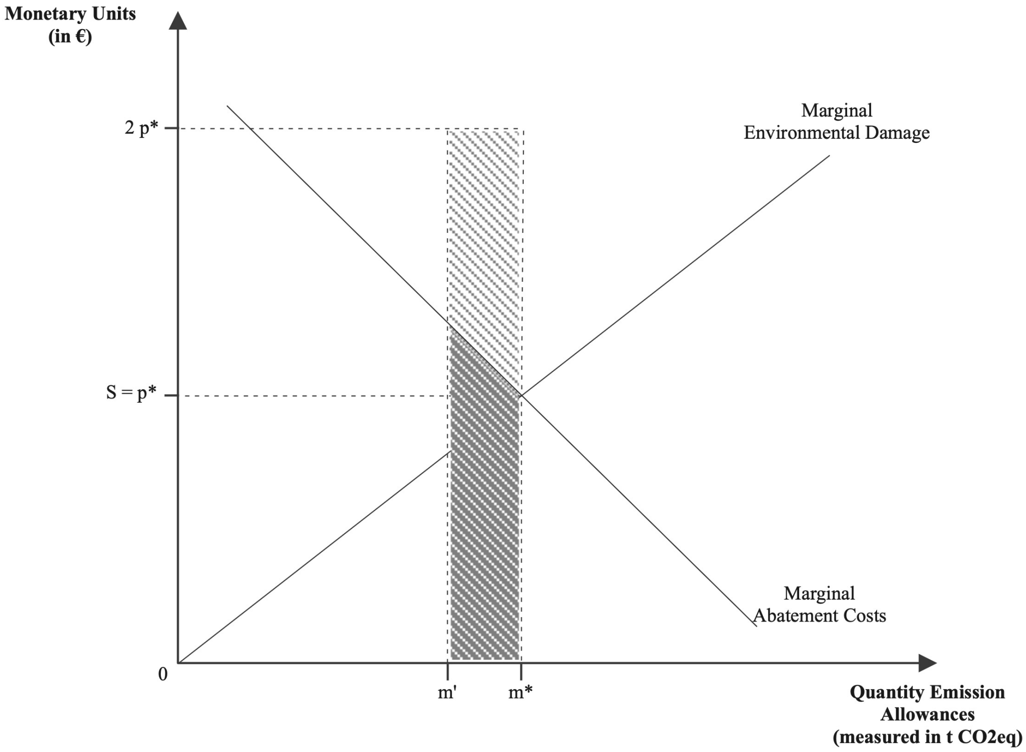

Figure 9: Net cost perspective for companies in the excess emission abatement scenario

3.2.3 Incentives for Excess Reduction – First & Second Order Condition

Given the net cost function above, when will a company decide to control emissions up to a level m' with the condition $m' < m^*$, thus realising the strong version of the Porter hypothesis? The model's core lies in the relationship between the additional benefits $AB_j(m')$ and the additional costs of removal $AC_j(m')$. Since each firm must bear the costs of $C_j(m^*)$ for regulation in any case, the incentive results from the ratio between additional costs and benefits. This brings us to the first-order condition:

Under the introduction of a market-based subsidy, a company will decide to abate emissions above the efficient level if the additional benefit is greater or equal to the additional cost.

$$AB_j(m') \geq AC_j(m')$$

$$2p^*(m^*-m') \geq \int_{m'}^{m^*} MAC$$

The first-order condition is sufficient and necessary. A company will only save emissions above the efficient level if it can cover the costs of investments made with the subsidy and the proceeds from the sale of allowances.

Whether the first-order condition holds and companies will make the necessary investments to remove emissions also depends on how elastic a company's abatement costs are to a reduction in the number of emissions. If the percentage change in abatement costs is greater than the percentage change in the number of emissions, then the marginal removal cost function is elastic. Thus, reducing the emission level from m^* to m' would lead to a higher percentage change in the abatement price. This case is illustrated in Figure 10. If the percentage change in removal costs is smaller than in emission level, we speak of an inelastic function. The following applies to the calculation of elasticities:

$$\varepsilon_m(p) = \left|\frac{\frac{\partial p}{p}}{\frac{\partial m}{m}}\right|$$

$$\varepsilon_m(p) = \left|\frac{\partial p}{\partial m}\frac{m}{p}\right|$$

The marginal abatement cost function is inelastic if the elasticity is $0 < \varepsilon < 1$. For values with $\varepsilon > 1$, the function is said to have high elasticity. In the case shown in Figure 10, where the marginal abatement cost responds elastically to the reduction of the emission quantity, it is conceivable that the first-order condition does not apply. The additional costs $AC_j(m')$ could be greater than the additional benefits $AB_j(m')$ in the case shown since the removal function approaches the emission level m' asymptotically. With this simple representation of the model, no precise statements can be made about the exact level of elasticity at which the first-order condition no longer applies. In generalised terms, however, it can be said that for functions with $0 < \varepsilon \leq 1$, the subsidy delivers the best results. For all elasticity values below 1, the percentage change in costs is smaller than in emissions. This brings us to the second-order condition:

A firm will choose to abate beyond the efficient emission level if the marginal abatement cost function responds inelastically to emission quantity changes. The incentive effect is highest for inelastic functions.

It holds $0 < \varepsilon \leq 1$.

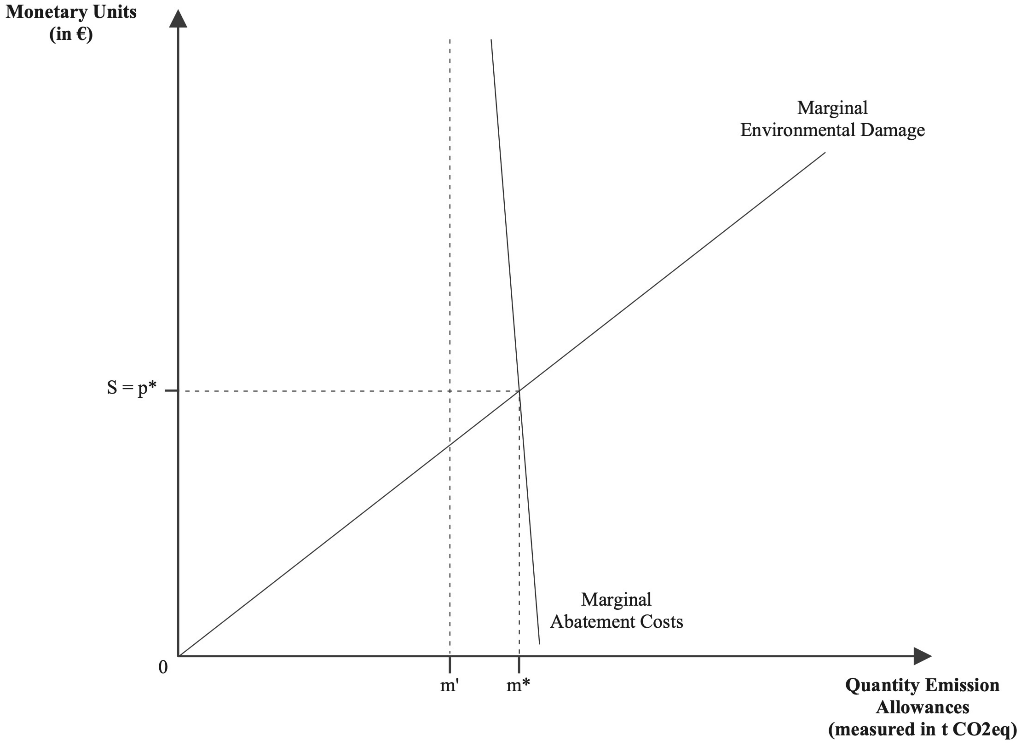

Figure 10: Elastic marginal abatement cost function in the subsidy scenario

The condition of the second order is sufficient but not necessary. The effect of the subsidy is higher when the sensitive costs react less to a reduction in emissions. Companies with elastic marginal abatement costs can also fulfil the first-order condition.

3.2.4 Impact on the Porter Hypothesis

Assuming that companies in the EU fulfil at least the first-order condition, the question arises whether introducing the subsidy can lead to realising the strong version of the Porter hypothesis. We recall that the strong version states that the „regulation induces innovation whose benefits exceed its costs, making the regulation socially desirable, even ignoring the environmental problems it was designed to solve" (Jaffe & Palmer, 1997, p. 611)., i.e., improving economic performance as well as limiting and reducing the environmental pollution. Thus, the regulation must benefit society while fulfilling the following conditions to fulfil the strong version of the Porter hypothesis. First, the statute must trigger innovation that, on the one hand, offsets the costs of the introduced regulation for companies and, on the other hand, promotes economic productivity and thus creates a positive net benefit. In addition to this condition, regulation must, secondly, also minimise the environmental damage caused by pollution.

This can be represented as a utility maximisation problem, shown below. Three functional values are included in the calculation. First, the benefit from the reduction of the pollution level (removal of external effects) is described by the function $D_{net}(m')$. The following applies to this function:

$$D_{net}(m') = \int_{m'}^{m*} MD$$

The second value that enters the utility calculus is the economy's productivity under the reduced emission level m'. Productivity is noted as $y(m')$ in the maximisation calculus. In third place are the net costs $NC(m')$ of implementing environmental regulation for businesses, which have already been described in 3.2.2. Since we consider society as a whole, the aggregated net costs are used here. We get:

$$NC(m') = \sum_{j=1}^{n} NC_j(m')$$

$$with$$

$$C(m*) = \sum_{j=1}^{n} C_j(m*),\ AB(m') = \sum_{j=1}^{n} AB_j(m') \text{ and } AC(m') = \sum_{j=1}^{n} AC_j(m')$$

Overall, we arrive at the following utility maximisation problem:

$$max\ \mu(m') = D_{net}(m') + y(m') - NC(m')$$

$$max\ \mu(m') = D_{net}(m') + y(m') - C(m*) + AB(m') - AC(m')$$

with the constraints

$$AB(m') - AC(m') \geq 0$$

$$D_{net}(m') > 0$$

$$y(m') - C(m*) \geq 0$$

The first condition does not need to be explained further, as it is the first-order condition already described in the previous section. It is a necessary and sufficient condition for emission savings to occur under the new market-based subsidy in the first place.

The second condition describes the benefit of additional emission savings and, thus, the reduction of negative externalities. This condition is always fulfilled if $m' < m^*$, i.e., whenever emissions are saved above efficiency. Therefore, the benefit from emission savings for the level m' is necessarily positive.

The core of the utility maximisation problem lies in the third and last condition. It describes that aggregate productivity under emission level m' is greater than the costs of environmental regulation. It is impossible to say precisely whether this condition applies, as no data are available. However, it is based on several assumptions. First, as mentioned in section 3.2.1, the marginal abatement costs of the companies are based on the so-called engineering model. Accordingly, the abatement costs reflect all investments that must be made to reduce the emission quantity from m^* to m'. Secondly, in Chapter 2, Section 2.2.3, Dechezleprêtre and Sato (2017) examined the research and found „that regulation-induced environmental innovations tend to replace other innovations, leaving the overall level of innovation unchanged" (Dechezleprêtre et al., 2021, p. 199). Behind the condition $y(m') - C(m^*) \geq 0$ is the following hypothesis: If a company fulfils the first-order condition, the costs for the excess emission savings $AC(m')$ can be entirely covered by the additional benefits $AB(m')$ (as shown in Figure 9). This allows the abating firms to make productivity-enhancing investments in addition to emission-saving investments that would remain on track under non-subsidised regulation. At this point, it should be noted that the last condition cannot be proven beyond doubt. The following concluding remark can be drawn:

> *The strong version of the Porter hypothesis is fulfilled if firms under subsidised emissions abatement invest in productivity-enhancing innovations that add value that outweighs the remaining costs of the EU-ETS.*

At first glance, this statement does not add new value to the discussion about the strong version of Porter's hypothesis. What contribution does the subsidy make to this condition? First and foremost, the subsidy enables companies to make productivity-enhancing investments without incurring additional costs. At the same time, this does not happen at the expense of the environment. The environment also benefits from the additional emission savings. However, the companies receive back the abatement investments they have made and can thus concentrate on the originally planned investments.

3.2.5 Further Framework Specifications

It has now been written in detail about how the subsidy is structured, which conditions must be fulfilled for additional emission savings to occur in companies and to what extent the newly introduced regulation supports the strong version of the Porter hypothesis. Nevertheless, questions remain unanswered, which further framework specifications will clarify in the following section. These specifications include (1) the determination of the efficient emissions quantity as a benchmark for additional savings, (2) the handling of freely allocated allowances and companies at risk of carbon leakage, and (3) the financing of the newly introduced subsidy.

The first question to be clarified revolves around determining the efficient emission level at the company level. While the regulator sets the efficient emission level m^* at the aggregate level, this level differs for the individual companies from the company perspective. However, since the subsidy is only paid out for savings above the efficient level, this level must be set for the companies. While in the case of the distribution of free certificates, the 10% most efficient companies are taken as a benchmark, in the case of the subsidy, a more individual approach can be chosen. A possible proposal: The efficient level of emissions is measured against a company's emissions from the previous year. Each emission reduction compared to the previous year is rewarded with a subsidy. Three further aspects need to be considered. First, the number of emission allowances or the cap on emissions is reduced by 2.2% each year, i.e. the efficiency level in the model shifts by this amount every year. Since the subsidy relates to emission savings above the efficient level, the payment should be made for any reduction greater than 2.2% compared to the previous year. Second, such measurement requires detailed and third-party verified measurement of operational emissions. However, contrary to the intuitive assumption, this would only minimally increase the transaction costs of companies under the current regulation. This is because, in 2019, the European Commission already required companies regulated by the EU-ETS to provide detailed operational emissions measurement and third-party verification ((EU) 2020/2085, 2020). However, these reports measure total emissions, which brings us to the third point. Thirdly, this information on emission levels needs to be adjusted to the companies' output. Companies should not qualify for the subsidy due to lower production and, consequently, lower emissions. The reported company emissions need to be adjusted accordingly.

Another issue that needs to be addressed in more detail is the treatment of freely allocated allowances and the eligibility for the subsidy of companies on the carbon leakage list. As explained in section 1.1.4, companies classified as carbon leakage vulnerable, i.e. companies where the cost is 100% of their allowances, receive them for free. All other industrial installations can qualify for free allocation through a benchmark system. The market-based subsidy can be used as a transitional instrument, i.e. the listed companies can also receive the subsidy if they reduce emissions according to the scheme described above. This can help vulnerable companies transition to lower-emission production and contribute to slowly phasing out the entire free allocation by the end of Phase IV, thus achieving the EU's ambitious climate targets. Behind this hypothesis lies the assumption that the innovation during one trading period helps reduce the emissions abatement costs for the next period. This process is illustrated in Figure 11. If the abatement costs decrease enough, the innovative companies are no longer at risk of carbon leakage. The described effect is debated and controversial in the literature.

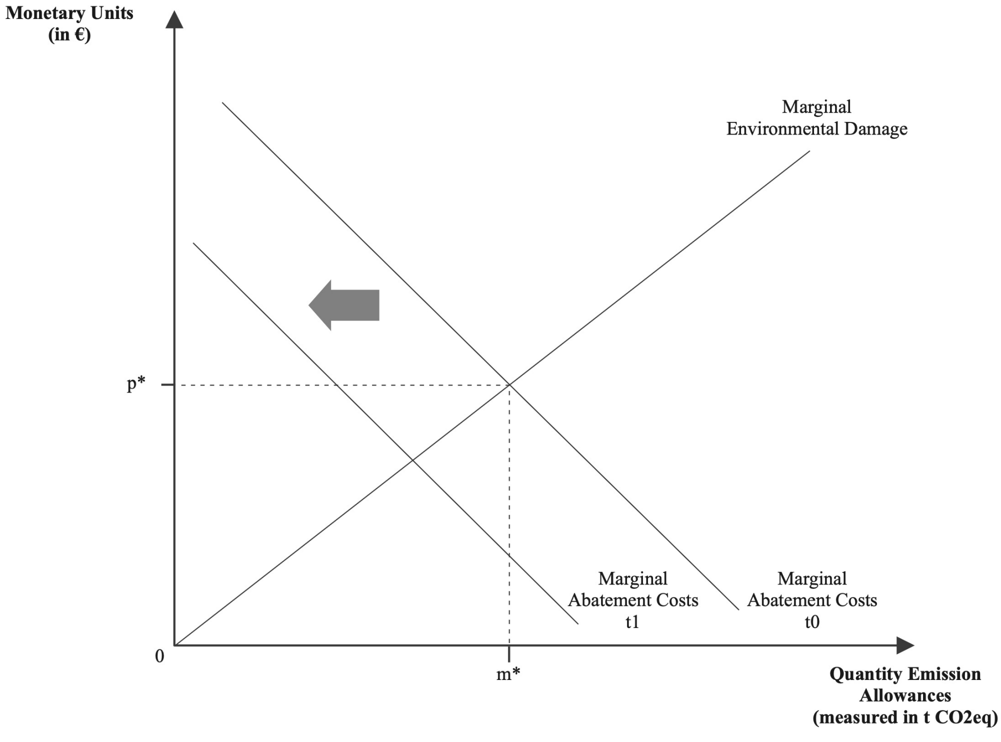

Figure 11: Effect of innovations on the marginal abatement cost curve

Authors such as Downing and White (1986), Milliman and Prince (1989) or Jung et al. (1996) assume that technological innovations reduce the costs of emission abatement, as shown in Figure 11. Baumann et al. (2008) write that this assumption is flawed, and that reducing marginal abatement costs only applies to end-of-pipe innovations. However, according to Baumann et al. (2008), many desirable technological innovations increase marginal abatement costs. Amir et al. (2008) confirm that there is indeed a downward shift in marginal abatement costs for end-of-pipe innovations. For other innovations, the development of costs depends primarily on the type of regulation and its stringency. Within the framework of this thesis, the question of companies at risk of carbon leakage cannot be definitively clarified and therefore offers material for future research. One possibility, however, would be to focus innovation on end-of-pipe technologies in particular.

To understand the financing issue, it is first necessary to have a rough idea of how much revenue the EU-ETS receives from the allowances auctions and what this revenue is spent on in the EU-27 countries. According to the European Environment Agency (2023), the total revenue from the auctions amounted to €31 billion in 2021, of which €25 billion was paid out to member states and the remaining €6 billion was invested in the Innovation Fund and the Modernisation Fund (European Environment Agency, 2023). Member states must invest at least 50% of the auction revenues in climate and energy-related projects. These projects include, for example, GHG emission mitigation, renewable energy, reforestation, and prevention of deforestation. In 2021, most member states fulfilled this obligation, and 76% of the revenues, or about 19 billion euros, were used for these purposes. For the implementation and success of the *Fit for 55* package, efforts on climate and energy must be significantly increased. The European Environment Agency (2023) also writes here that it is necessary to use the entire revenues of the ETS auctions for climate and energy-related projects. A proposal in the context of the funding issue for the subsidy could be an allocation of 25% of the revenues of the member states for the subsidy payment for emission-abating companies. With 2021 revenues of 25 billion euros, this would correspond to about 6.25 billion euros, just under 20% of the total revenues of 31 billion euros. But is 6 billion euros enough to pay for subsidies? How much emission savings can be expected under the proposed instrument? No reliable statements about potential emission reductions can be made, as the subsidy is a thought experiment that has not yet been the subject of scientific studies. According to the European Commission, emissions from regulated industries have decreased by about 35% between 2005 and 2021 (European Commission, 2021b), corresponding to an annual average of about 2.2%. With the introduction of the Market Stability Reserve in 2019, the average reductions were as high as 9% (European Commission, 2021b). Assuming that the subsidy is only paid out for savings above the efficient level described above, i.e. for any reduction more significant than 2.2%, various scenarios can be derived and calculated. The EU-ETS trading period 2020-21 is used as a reference for these scenarios. The average spot price for EU-ETS allowances in this period was €39.9 (IBISWorld, 2022). A total of 474 million allowances were sold during this period (European Environment Agency, 2022a).

In scenario 1, average emissions were reduced by 5% per year. Thus, the share of emission abatement to be compensated, after the deduction of 2.2%, is 2.8%, corresponding to 13.3 million additional emissions saved in the total trading volume. With the addition of the average price, the EU would have to pay around 529.6 million euros for the compensation. In scenario 2, emissions were reduced by 10%, and 36.9 million tonnes of CO_2 equivalents were abated beyond the efficient level. This means that 1.5 billion euros are needed to compensate for the 7.8% subsidy. In the third scenario, emissions are reduced by 20%, resulting in 84.4 million tonnes of CO_2 equivalents saved extra. This corresponds to a total subsidy disbursement of 3.4 billion euros. It has been shown that the subsidy for emission savings above the efficient emission level up to 20% abatement can be financed from 25% of the revenue from the member states' shares. This ensures that the costs of the subsidy do not outweigh the benefits from the previous chapter and that the conditions are still met.

4 Discussion

The model presented is based on assumptions and is very simply constructed. This also creates room for criticisms and weaknesses, briefly discussed in this chapter. Some problems and doubts can be eliminated, while further research is needed to clarify other questions. Overall, this section will address three points that create space for further discussion around implementing the proposed market-based subsidy. These points include (1) the transaction cost discussion, (2) the problem of excess supply in the case of high emission abatement by companies, and (3) the applicability of marginal cost theories in the environmental economics context.

The first problem addresses the issue of transaction costs. The introduction of such a subsidy entails a high level of bureaucracy. On the one hand, companies have to measure their emissions and have them verified by third parties. However, as described above, companies must do such reporting since 2019. The additional effort on the part of the companies consists of adjusting their emissions to the output, i.e. disclosing the emission intensity of their products. Most of the transaction costs arise on the side of the EU, which must first enact the necessary laws if such regulation is enforced. In addition, the reports of the companies must then be checked individually, and the compensation calculated and paid. This effort becomes very high with almost 8757 electricity and heat suppliers, industrial plants, and 371 airlines, even if we cannot assume every operator to apply for the subsidy. The high transaction costs of the subsidy could outweigh the social benefits and ensure that the Porter hypothesis loses its validity. However, this issue of transaction costs cannot be definitively resolved and may need to be further addressed in future research.

Another weakness of the subsidy is the problem of a surplus supply of emission allowances for emission savings. As explained above, the additional benefits $AB_j(m')$ of emission savings result from the subsidy paid out and the sale of the remaining emission allowances. Assuming that many companies reduce their emissions above the efficient emission level, the demand for carbon permits decreases. However, since the quantity of allowances offered remains the same, the prices for the EUAs fall. Under these conditions, the additional benefits $AB_j(m')$ would be reduced so that the first-order condition may no longer hold and the incentive for excessive emission savings are lost. But here, the model of Kwerel (1977) and the explanations of Perman (2003) provide a possible solution. In his article, Kwerel (1977) describes how companies falsely communicate higher abatement costs to the regulating authority to increase the distribution of allowances. In the problem, we are facing, and the situation described by Kwerel (1977), the supply of carbon allowances is higher than the demand, so the price should decrease. However, the subsidy itself prevents this price drop. This is because the existence of the subsidy raises the minimum level of the allowance price to $s^* = p$. The price of carbon permits cannot fall below the level of the subsidy that firms receive. If the price fell below s^*, many companies would buy the cheaper allowances to get the higher-valued subsidy more easily. Therefore, a price decline is not possible under the subsidy model.

Another point of criticism is the applicability of marginal cost considerations in an environmental-economic context. The model is based on a simplified assumption that pollution problems can be represented and solved by graphical and mathematical marginal considerations. The applicability of these economic models is also disputed in the literature. Kesicki and Ekins (2011) examine the applicability of marginal cost curves regarding potential weaknesses, shortcomings and problems in interpreting results using marginal costing. They find several areas for improvement in this method, particularly the need for adjustments for dynamic developments mentioned by Kesicki and Ekins (2011). Furthermore, the marginal cost model fails to include uncertainties in the calculation. On this basis, the authors draw up various recommendations for regulators. Accordingly, a marginal cost approach should never be used as a one-stop assessment criterion for environmental policies, and the assumptions behind it should be communicated transparently.

I am aware of the problems that the simple model of marginal costing brings and would like to emphasise one thing again. This thesis is not a policy recommendation. The model is too simple for that. But that is not the aim of this thesis. This thesis has looked at one possibility, a thought experiment of how emissions regulation and the shift to a greener economy can be attractive to businesses without being at the expense of the environment. It is a (simplified) model under which companies can see regulation as an opportunity to become greener and thereby get the chance to grow as a company, both in the environmental and economic sense, regarding productivity growth. The paper aspires to be an impulse for others to engage with the model at a deeper level. For this purpose, a marginal cost approach is sufficient. Kesicki and Ekins (2011) also write that „a MAC curve is a simple and useful illustrative tool to engage various stakeholders in the debate about climate change mitigation" (Kesicki & Ekins, 2012, p. 233). Understood in this context, the proposed model can stimulate discussion about regulatory adjustments. This work has shown that this discussion is essential in the context of growing economic challenges for regulated companies.

Conclusion

This paper has addressed the research question: Can a market-based subsidy in combination with tradable emission permits contribute to the achievement of ambitious climate targets without placing an additional burden on companies? To answer this question, hypotheses were first formulated on the causes of price increases for EUAs and the consequences of carbon pricing for regulated companies. The proposed model of a market-based subsidy is based on a simplified representation of the marginal cost approach.

The first chapter examined the relationship between the increase in EUA prices observed since 2021 and the energy crisis of 2021-23. It was hypothesised and investigated whether the increase in the price of EU allowances can be attributed to the exogenous price shock of energy commodities such as gas and oil. It was observed that inflated gas prices, in particular, increased demand for coal in the energy sector. Due to fuel switching in the energy sector from gas to coal, the demand for emission certificates increased, which led to rapid increases for these. However, an analysis of selected literature revealed that the price-driving effect of energy on gas could only partially explain the observed increases. Other price fundamentals, such as institutional decisions (changing policies) and extreme weather events, also drive up the prices of EUAs. The first hypothesis was thus rejected but provided essential insights for the design of the presented instrument, especially concerning demand and time horizon.

The second chapter examined the hypothesis that the EU-ETS's carbon pricing harms regulated companies' competitiveness, location choice and investment decisions. The literature reviewed could not find any empirical evidence, mainly due to the low prevailing EUA prices between Phase I and III. The second hypothesis could thus neither be confirmed nor refuted, as the research results cannot be transferred to the currently prevailing price situation. At the same time, however, the study showed that further research is needed in this area. It also investigated how the EU-ETS promotes productivity and the shift towards a more sustainable economy. Under the terminological framework of Porter's hypothesis, previous research has demonstrated that investment in more sustainable technologies occurs but has not found evidence that implementing the EU-ETS positively impacts business productivity. Instead, investments in lower-emission technologies often replace planned productivity-enhancing investments.

Against the background of increasing scarcity of allowances due to the more substantial reduction of the emission cap under the Fit-for-55 package, the situation described above will remain the same. Even if the so-called CBAM attacks the problem of carbon leakage, companies will focus even more on investments in green technologies. Thus, the EU risks systematically replacing productivity gains with climate protection.

The third chapter presented an alternative to the EU's current scarcity policy. The modelling of the market-based subsidy showed, based on the marginal cost approach, that a market-based subsidy creates an incentive for companies to reduce emissions beyond the efficient level without incurring additional costs. The motivation for extra emission abatement exists if the additional benefits of these savings are greater than the additional costs (first order condition) and the net benefit is higher the more inelastic the marginal costs react to the emission reduction. Under the market-based subsidy model, additional environmental benefits can be created by incentivising companies to avoid emissions beyond the efficient level without imposing an extra burden on them. Assuming that companies invest in productivity-enhancing innovations under this model, the market-based subsidy model is socially acceptable. In financing such an instrument, it has been proposed to use part of the proceeds from the EUA auctions. Assuming stable prices, the potential emission savings could be financed from 25% of the EUA proceeds in different scenarios.

In the fourth chapter, possible limitations of the model were addressed. The problem of excess supply in the case of high emission abatement by companies could be eliminated within the framework of the model. The discussion about possible excessive transaction costs cannot be refuted beyond doubt. The implementation of environmental regulation is always associated with high transaction costs. The biggest weakness is the limited applicability of the model. I cannot deny that the implementation of the instrument proposed here is more complicated in reality than presented in this thesis. But this thesis did not claim to be a fully developed model from the beginning. The model is intended to provide an incentive to think outside the current EU policy and to look at alternative ideas (even if they find their inspiration in an article from 1977). After all, the EU-ETS was created according to exactly such a model.

And this is precisely where the prospects for further research lie. The model proposed here must be thought through further if it is really to be considered an alternative to the current policy. For example, the question of financing must be clarified in detail by experts from the financial sector. Currently, the answer is based on simple calculations with stable prices. We saw at the beginning of the thesis that these prices are by no means stable. The model has to be calculated in detail, and its incentives mentioned here must be examined empirically before it finds its way into politics. But to create this incentive, seriously consider the idea of such a subsidy and encourage further thinking; therein lies the actual value of this thesis. Because thinking ahead and continuing the EU's unique environmental instrument must not be abandoned under any circumstances. The discussion on sustainable growth must be pushed forward because carbon must continue to have a price. Nature must not pay that price - that much is clear. But innovation and productivity must not be the price we pay for decarbonising the Union.

List of References

AATOLA, P., M. OLLIKAINEN, and A. TOPPINEN, 2013. Price determination in the EU-ETS market: Theory and econometric analysis with market fundamentals [online]. *Energy Economics*, **36**, 380-395. Available from: 10.1016/j.eneco.2012.09.009

ALBEROLA, E., J. CHEVALLIER, and B. CHÈZE, 2008. Price drivers and structural breaks in European carbon prices 2005–2007 [online]. *Energy Policy*, **36**(2), 787-797. Available from: 10.1016/j.enpol.2007.10.029

AMIR, R., M. GERMAIN, and V. VAN STEENBERGHE, 2008. On the Impact of Innovation on the Marginal Abatement Cost Curve [online]. *Journal of Public Economic Theory*, **10**(6), 985-1010. Available from: 10.1111/j.1467-9779.2008.00393.x

BATTEN, J.A., G.E. MADDOX, and M.R. YOUNG, 2021. Does weather, or energy prices, affect carbon prices? [online]. *Energy Economics*, **96**, 105016. Available from: 10.1016/j.eneco.2020.105016

BAUMAN, Y., M. LEE, and K. SEELEY, 2008. Does Technological Innovation Really Reduce Marginal Abatement Costs? Some Theory, Algebraic Evidence, and Policy Implications [online]. *Environmental and Resource Economics*, **40**(4), 507-527. Available from: 10.1007/s10640-007-9167-7

BERTRAND, V., 2014. Carbon and energy prices under uncertainty: A theoretical analysis of fuel switching with heterogenous power plants [online]. *Resource and Energy Economics*, **38**, 198-220. Available from: 10.1016/j.reseneeco.2014.08.001

BÖHRINGER, C., E.J. BALISTRERI, and T.F. RUTHERFORD, 2012. *The Role of Border Carbon Adjustment in Unilateral Climate Policy: Insights from a Model-Comparison Study. The Harvard Project on Climate Agreements.* Discussion Paper [viewed 11 March 2023]. Available from: https://www.belfercenter.org/sites/default/files/files/publication/bohringer_dp54_v3-final.pdf

BÖHRINGER, C. and T.F. RUTHERFORD, 2008. Combining bottom-up and top-down [online]. *Energy Economics*, **30**(2), 574-596. Available from: 10.1016/j.eneco.2007.03.004

BORGHESI, S., C. FRANCO, and G. MARIN, 2020. Outward Foreign Direct Investment Patterns of Italian Firms in the European Union's Emission Trading Scheme* [online]. *The Scandinavian Journal of Economics*, **122**(1), 219-256. Available from: 10.1111/sjoe.12323

BRANGER, F., P. QUIRION, and J. CHEVALLIER, 2016. Carbon Leakage and Competitiveness of Cement and Steel Industries Under the EU-ETS: Much Ado About Nothing [online]. *The Energy Journal*, **37**(3), 109-135 [viewed 13 March 2023]. Available from: 10.5547/01956574.37.3.fbra

BROHÉ, A. and S. BURNIAUX, 2015. The impact of the EU-ETS on firms' investment decisions: evidence from a survey [online]. *Carbon Management*, **6**(5-6). Available from: 10.1080/17583004.2015.1131384

CHAN, H.S., S. LI, and F. ZHANG, 2012. Firm Competitiveness and the European Union Emissions Trading Scheme [online]. *SSRN Electronic Journal*, **63**. Available from: 10.2139/ssrn.2167298

CHEVALLIER, J., 2012. *Econometric Analysis of Carbon Markets. The European Union Emissions Trading Scheme and the Clean Development Mechanism.* Dordrecht: Springer Netherlands. SpringerLink Bücher.

CHRISTIANSEN, A.C., A. ARVANITAKIS, K. TANGEN, and H. HASSELKNIPPE, 2005. Price determinants in the EU emissions trading scheme [online]. *Climate Policy*, **5**(1), 15-30. Available from: 10.1080/14693062.2005.9685538

CONRAD, C., D. RITTLER, and W. ROTFUß, 2012. Modeling and explaining the dynamics of European Union Allowance prices at high-frequency [online]. *Energy Economics*, **34**(1), 316-326. Available from: 10.1016/j.eneco.2011.02.011

COUNCIL OF THE EUROPEAN UNION AND EUROPEAN COUNCIL, 2023. *Infographic - Fit for 55: reform of the EU emissions trading system* [online]. 29 March 2023, 12:00 [viewed 20 April 2023]. Available from: https://www.consilium.europa.eu/en/infographics/fit-for-55-eu-emissions-trading-system/

DECHEZLEPRÊTRE, A., C. GENNAIOLI, R. MARTIN, M. MUÛLS, and T. STOERK, 2021. *Searching for carbon leaks in multinational companies.* Working Paper No. 165. Available from: https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2019/01/working-paper-165-Dechezlepretre-et-al-Feb-2021.pdf

DECHEZLEPRÊTRE, A. and M. SATO, 2017. The Impacts of Environmental Regulations on Competitiveness [online]. *Review of Environmental Economics and Policy*, **11**(2), 183-206 [viewed 2023.03-07]. Available from: 10.1093/reep/rex013

DELARUE, E., K. VOORSPOOLS, and W. D’HAESELEER, 2008. Fuel Switching in the Electricity Sector under the EU-ETS: Review and Prospective [online]. *Journal of*

Energy Engineering, **134**(2), 40-46. Available from: 10.1061/(ASCE)0733-9402(2008)134:2(40)

DOWNING, P.B. and L.J. WHITE, 1986. Innovation in pollution control [online]. *Journal of Environmental Economics and Management*, **13**(1), 18-29. Available from: 10.1016/0095-0696(86)90014-8

EUROPEAN COMMISSION, 2018. *Commission Implementing Regulation (EU) 2018/2067 of 19 December 2018 on the verification of data and on the accreditation of verifiers pursuant to Directive 2003/87/EC of the European Parliament and of the Council. (EU) 2018/2067.*

EUROPEAN COMMISSION, 15 Dec. 2020. *COMMISSION IMPLEMENTING REGULATION (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012. (EU) 2020/2085.*

EUROPEAN COMMISSION, 2021. *Emissions cap and allowances* [online] [viewed 26 February 2023]. Available from: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_en

EUROPEAN COMMISSION, 2021. *EU Emissions Trading System (EU-ETS)* [online] [viewed 20 April 2023]. Available from: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

EUROPEAN COMMISSION, 14 Dec. 2022. *REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL. on the Functioning of the European carbon market in 2021 pursuant to Articles 10(5) and 21(2) of Directive 2003/87/EC (as amended by Directive 2009/29/EC and Directive (EU) 2018/410).* Brussels [viewed 26 February 2023]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0516

EUROPEAN COMMISSION AND DIRECTORATE-GENERAL FOR MOBILITY AND TRANSPORT, 2022. *EU transport in figures. Statistical pocketbook 2022:* Publication Office.

EUROPEAN COURT OF AUDITORS, 2020. *The EU's emissions trading system. Free allocation of allowances needed better targeting.* Luxembourg: Publications Office of the European Union. Special report. No 18, 2020.

EUROPEAN ENVIRONMENT AGENCY, 2022. *European Union Emissions Trading System (EU-ETS) allowances auctioned or sold in 2020 and 2021, by country (in millions)* [online]. *Graph* [viewed 20 April 2023]. Available from:

https://www.statista.com/statistics/1329545/eu-ets-allowances-auctioned-or-sold-by-country/

EUROPEAN ENVIRONMENT AGENCY, 2022. *Europe's changing climate hazards. An index-based interactive EEA report.* Luxembourg: Publications Office of the European Union. EEA report. 15/2021.

EUROPEAN ENVIRONMENT AGENCY, 2023. *Use of auctioning revenues generated under the EU Emissions Trading System* [online]. 1 February 2023, 12:00 [viewed 20 April 2023]. Available from: https://www.eea.europa.eu/ims/use-of-auctioning-revenues-generated

EUROPEAN UNION, 2010. Commission Regulation (EU) No 1031/2010 of 12 November 2010 on the timing, administration and other aspects of auctioning of greenhouse gas emission allowances pursuant to Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowances trading within the Community Text with EEA relevance [online]. Commission Regulation (EU) No 1031/2010. *Official Journal of the European Union*, **53**, 1-41. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2010:302:FULL&from=EN

EUROPEAN UNION, 2017. AGREEMENT - between the European Union and the Swiss Confederation on the linking of their greenhouse gas emissions trading systems [online]. *Official Journal of the European Union*, **60**, 3-26. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:22017A1207(01)&from=EN

EUROPEAN UNION, 2019. Commission Delegated Decision (EU) 2019/708 of 15 February 2019 [online]. supplementing Directive 2003/87/EC of the European Parliament and of the Council concerning the determination of sectors and subsectors deemed at risk of carbon leakage for the period 2021 to 2030 (Text with EEA relevance.). *Official Journal of the European Union*, **62**, 20-26. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019D0708&from=EN

EUROPEAN UNION, 2019. Commission Implementing Regulation (EU) 2019/1842 of 31 October 2019 [online]. laying down rules for the application of Directive 2003/87/EC of the European Parliament and of the Council as regards further arrangements for the adjustments to free allocation of emission allowances due to activity level changes. *Official Journal of the European Union*, **62**, 20-24. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1842&from=EN

EUROPEAN UNION, 2021. Commission Implementing Regulation (EU) 2021/447 of 12 March 2021 [online]. determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council (Text with EEA relevance). *Official Journal of the European Union*, **64**, 29-34. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0447&qid=1677942409303&from=en

FELBERMAYR, G. and S. PETERSON, 14 Apr. 2020. *Economic assessment of Carbon Leakage and Carbon Border Adjustment* [viewed 21 February 2023]. Available from: https://policycommons.net/artifacts/1337187/economic-assessment-of-carbon-leakage-and-carbon-border-adjustment/1944860/

FISCHER, C. and R.G. NEWELL, 2008. Environmental and technology policies for climate mitigation [online]. *Journal of Environmental Economics and Management*, **55**(2), 142-162. Available from: 10.1016/j.jeem.2007.11.001

GRAY, W.B. and R.J. SHADBEGIAN, 2001. *Plant Vintage, Technology, and Environmental Regulation. Working Paper Series.* Working Paper # 01-04 [viewed 10 March 2023]. Available from: https://ageconsearch.umn.edu/record/280793/

GREENSTONE, M., J.A. LIST, and C. SYVERSON, 2012. *The Effects of Environmental Regulation on the Competitiveness of U.S. Manufacturing. CEEPR WP 2012-013* [viewed 10 March 2023]. Available from: https://ceepr.mit.edu/wp-content/uploads/2021/09/2012-013.pdf

HAMILTON, J.D., 2009. Causes and Consequences of the Oil Shock of 2007–08 [online]. *Brookings Papers on Economic Activity*, **40**(1), 215-261. Available from: https://www.brookings.edu/wp-content/uploads/2016/07/2009a_bpea_hamilton-1.pdf

IBISWORLD, 2022. *Average closing spot prices of European Emission Allowances (EUA) from 2010 to 2021 (in euros per metric ton of carbon dioxide)* [online]. *Graph* [viewed 20 April 2023]. Available from: https://www.statista.com/statistics/1329581/spot-prices-european-union-emission-trading-system-allowances/

INTERNATIONAL ENERGY AGENCY. European Union 2020 - Energy Policy Review.

INTERNATIONAL ENERGY AGENCY, 2022. *Coal 2022. License: CC BY 4.0.* Paris [viewed 4 April 2023]. Available from: https://www.iea.org/reports/coal-2022

INTERNATIONAL ENERGY AGENCY, 2022. *Renewables 2022.* Paris [viewed 4 April 2023]. Available from: https://www.iea.org/reports/renewables-2022

INTERNATIONAL ENERGY AGENCY, 2022. *World Energy Outlook 2022. Available from:* https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

IETA, 2022. *Average carbon price expectations worldwide from 2022 to 2030, by trading system (in euros per metric ton of carbon dioxide)* [online]. *Graph* [viewed 20 April 2023]. Available from: https://www.statista.com/statistics/1334906/average-carbon-price-projections-worldwide-by-region/

JAFFE, A.B. and K. PALMER, 1997. Environmental Regulation and Innovation: A Panel Data Study [online]. *Review of Economics and Statistics*, **79**(4), 610-619. Available from: 10.1162/003465397557196

JOLTREAU, E. and K. SOMMERFELD, 2019. Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms' competitiveness? Empirical findings from the literature [online]. *Climate Policy*, **19**(4), 453-471. Available from: 10.1080/14693062.2018.1502145

JUNG, C., K. KRUTILLA, and R. BOYD, 1996. Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives [online]. *Journal of Environmental Economics and Management*, **30**(1), 95-111. Available from: 10.1006/jeem.1996.0007

KESICKI, F. and P. EKINS, 2012. Marginal abatement cost curves: a call for caution [online]. *Climate Policy*, **12**(2), 219-236. Available from: 10.1080/14693062.2011.582347

KOCH, N. and H. BASSE MAMA, 2016. European Climate Policy and Industrial Relocation: Evidence from German Multinational Firms [online]. *SSRN Electronic Journal* [viewed 11 March 2023]. Available from: 10.2139/ssrn.2868283

KUIK, O., 2014. *International competitiveness and leakage. A case study of the European steel industry.* Amsterdam [viewed 11 March 2023]. Available from: https://www.cecilia2050.eu/system/files/Kuik%20(2014)_International%20competitiveness%20and%20leakage_0.pdf

KWEREL, E., 1977. To Tell the Truth: Imperfect Information and Optimal Pollution Control [online]. *The Review of Economic Studies*, **44**(3), 595-601 [viewed 8 March 2023]. Available from: 10.2307/2296911

LAZZINI, S., Z. OCCHIPINTI, A. PARENTI, and R. VERONA, 2021. Disentangling economic crisis effects from environmental regulation effects: Implications for sustainable development [online]. *Business Strategy and the Environment*, **30**(5), 2332-2353. Available from: 10.1002/bse.2749

LUNDGREN, T., P.-O. MARKLUND, E. SAMAKOVLIS, and W. ZHOU, 2015. Carbon prices and incentives for technological development [online]. *Journal of environmental management*, **150**, 393-403. Available from: 10.1016/j.jenvman.2014.12.015

MANSANET-BATALLER, M. and A. PARDO, 2009. Impacts of regulatory announcements on CO 2 prices [online]. *The Journal of Energy Markets*, **2**(2), 1-33. Available from: 10.21314/JEM.2009.019

MANSANET-BATALLER, M., A. PARDO, and E. VALOR, 2007. CO2 Prices, Energy and Weather [online]. *The Energy Journal*, **28**(3). Available from: 10.5547/ISSN0195-6574-EJ-Vol28-No3-5

MARTIN, R., M. MUÛLS, L.B. de PREUX, and U.J. WAGNER, 2014. Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme [online]. *American Economic Review*, **104**(8), 2482-2508 [viewed 13 March 2023]. Available from: 10.1257/aer.104.8.2482

MILLIMAN, S.R. and R. PRINCE, 1989. Firm incentives to promote technological change in pollution control [online]. *Journal of Environmental Economics and Management*, **17**(3), 247-265. Available from: 10.1016/0095-0696(89)90019-3

NAEGELE, H. and A. ZAKLAN, 2019. Does the EU-ETS cause carbon leakage in European manufacturing? [online]. *Journal of Environmental Economics and Management*, **93**, 125-147. Available from: 10.1016/j.jeem.2018.11.004

PERMAN, R., Y. MA, J. MCGILVRAY, and M. COMMON, 2010. *Natural resource and environmental economics.* 3. ed., [Nachdr.]. Harlow: Pearson Addison Wesley.

PETRICK, S. and U.J. WAGNER, 2014. The Impact Of Carbon Trading On Industry: Evidence From German Manufacturing Firms [online]. *SSRN Electronic Journal* [viewed 10 March 2023]. Available from: 10.2139/ssrn.2389800

PORTER, M.E. and C. VAN DER LINDE, 1995. Toward a New Conception of the Environment-Competitiveness Relationship [online]. *Journal of Economic Perspectives*, **9**(4), 97-118. Available from: 10.1257/jep.9.4.97

RUBASHKINA, Y., M. GALEOTTI, and E. VERDOLINI, 2015. Environmental regulation and competitiveness: Empirical evidence on the Porter Hypothesis from European manufacturing sectors [online]. *Energy Policy*, **83**, 288-300. Available from: 10.1016/j.enpol.2015.02.014

SARTOR, O., 2013. Carbon Leakage in the Primary Aluminium Sector: What Evidence after 6.5 Years of the EU-ETS? [online], **13**(106) [viewed 13 March 2023]. Available from: 10.2139/ssrn.2205516

SWISS FEDERAL COUNCIL, 30 Nov. 2012. *Ordinance on the Reduction of CO2 Emissions. CO2 Ordinance*.

TWIDALE, S., K. ABNETT, and N. CHESTNEY, 2023. *EU carbon hits 100 euros taking cost of polluting to record high* [online]. 21 February 2023, 12:00 [viewed 20 April 2023]. Available from: https://www.reuters.com/markets/carbon/europes-carbon-price-hits-record-high-100-euros-2023-02-21/

VAN RUIJVEN, B. and D.P. VAN VUUREN, 2009. Oil and natural gas prices and greenhouse gas emission mitigation [online]. *Energy Policy*, **37**(11), 4797-4808. Available from: 10.1016/j.enpol.2009.06.037

VIELLE, M. and L. VIGUIER, 2007. On the climate change effects of high oil prices [online]. *Energy Policy*, **35**(2), 844-849. Available from: 10.1016/j.enpol.2006.03.022

WAGNER, U.J., M. MUÛLS, R. MARTIN, and J. COLMER, 1 Apr. 2014. *The Causal Effects of the European Union Emissions Trading Scheme: Evidence from French Manufacturing Plants.* The Fifth World Congress of Environmental and Resources Economists, Istanbul, Turkey [viewed 10 March 2023]. Available from: https://conference.iza.org/conference_files/EnvEmpl2014/martin_r7617.pdf

WILSON, I.A.G. and I. STAFFELL, 2018. Rapid fuel switching from coal to natural gas through effective carbon pricing [online]. *Nature Energy*, **3**(5), 365-372. Available from: 10.1038/s41560-018-0109-0

WORLD BANK, 2021. *Industry (including construction), value added (% of GDP) - European Union* [online]. 2021 [viewed 18 February 2023]. Available from: https://data.worldbank.org/indicator/NV.IND.TOTL.ZS?end=2021&locations=EU&start=1991&view=chart

WORLD BANK, 2021. *Manufacturing, value added (% of GDP) - European Union* [online]. 2021 [viewed 18 February 2023]. Available from: https://data.worldbank.org/indicator/NV.IND.TOTL.ZS?end=2021&locations=EU&start=1991&view=chart