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Assessing the effect of CBAM on the Nitrogen Fertilizer Industry: A 2030 Outlook

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Acknowledgement

We conclude our time at NMBU with the submission of this master's thesis, and thus reflect on the past two years filled with growth and learning. The spring semester dedicated to writing has been challenging, enjoyable and educative. Writing the thesis has given us the opportunity to expand our knowledge in climate and trade economics through specialization in a topic of high relevance.

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We hope our master's thesis will give insight into CBAM and the fertilizer industry, and shed light on the potential impact specific climate measures can have on global emissions. Lastly, we take full responsibility for any inaccuracies or ambiguities present in the thesis.

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Summary

The European Union's (EU) Carbon Border Adjustment Mechanism (CBAM) will be effective from 2026, as a measure to reduce carbon leakage and ensure European competitiveness with the phase-out of free allowances in the Emission Trading System (ETS). This thesis investigates the potential effect of introducing CBAM on the nitrogen fertilizer industry by developing an ex ante partial equilibrium model towards 2030. The analysis examines free allowances while introducing CBAM. The thesis finds that CBAM will protect domestic industry more than free allowances but will in return increase fertilizer prices. The policy will give relatively higher costs for producers with a more carbon intensive production, which will cause suppliers outside the EU to leave the EU market. The analysis also shows that reducing free allowances in the ETS in combination with CBAM will reduce global emissions by 1,5%. For further EU emission reduction, it is necessary to shift to renewable energy solutions. The thesis therefore also studies the inclusion of the Renewable Energy Directive (RED III), which requires 42% of hydrogen, an important input for fertilizer production, to derive from renewable energy. Combining the reduction of free allowances in the ETS, CBAM, and RED III proves effective in reducing climate emissions and the risk of carbon leakage, only if the costs of green technology decrease. If costs of green technology remain high according to today's prediction, the introduction of CBAM will have a negative effect on the EU industry and have zero effect on emissions.

Keywords: *CBAM, ETS, nitrogen fertilizer, carbon price, carbon leakage, trade, GHG emissions, RED III, EU, Norway, partial equilibrium model, climate change, climate economics, 2030.*

Glossary

Acronym or Term	**Definition or Meaning**
BCA	Border Carbon Adjustment
BTU	British Thermal Units
CBAM	Carbon Border Adjustment Mechanism
CNY	Chinese yuan to euros
CGE	Computable General Equilibrium
EEA	European Economic Area
ETS	Emission Trading System
EU	European Union
FAO	Food and Agriculture Organization
FC	Fixed Cost
GATT	General Agreement on Tariffs and Trade
GHG	Greenhouse Gas
GJ	Gigajoule
IEA	International Environmental Agreement
IPCC	International Panel of Climate Change
IRA	Inflation Reduction Act
M	Million
MAC	Marginal Abatment Cost
MC	Marginal Cost
MFN	Most Favored Nation
MMbtu	Million British Thermal Units
MR	Marginal Revenue
MSR	Market Stability Reserve
MWh	Megawatt hour
N	Nitrogen
NT	National Treatment
OBA	Output Based Allocation

RED	Renewable Energy Directive
ROW	Rest of the World
t	tonne
TC	Total Cost
Third country	Country outside of the EU/EEA
UN	United Nations
VC	Variable Cost
WTO	World Trade Organization

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1. Introduction

The 2023 climate report from the International Pannel of Climate Change (IPCC) concludes that the world is no longer waiting for global warming, it is currently facing it. Changes in the atmosphere and the oceans have already caused extreme climate and weather changes in all regions of the globe (IPCC, 2023, p.5). In order to limit global warming to well below 2 degrees, the world requires deep and urgent mitigation reduction in all sectors this decade (IPCC, 2023, p. 20).

The European Union (EU) is at the forefront of climate mitigation, and a significant driving force for international climate policies. In July 2021, the European Commission presented the "Fit for 55" package. The initiative consists of different legislative proposals for reducing greenhouse gas (GHG) emissions by at least 55% within 2030 compared to 1990 levels and becoming climate neutral by 2050 (European Commission, 2021, p.1).

Despite EU's ambitious climate goals on GHG emission reduction, a pressing concern emerges regarding the risk of carbon leakage. This phenomenon occurs when carbon intensive production is reallocated to regions with less stringent environmental regulations to avoid emission costs from CO_2-pricing. In the short term, this risk also raises concerns about maintaining competitiveness in the global market. High CO_2 prices in the EU could potentially put EU industries at a competitive disadvantage compared to their counterparts in regions with lower carbon prices or fewer regulations. Such differences in carbon pricing and environmental standards may increase supply of carbon-intensive imports from outside the EU, weakening the impact of the EU's carbon reduction measures and possibly leading to a shift in global emissions rather than actual reductions (Zhang, 2012, p.226-228).

The EU's Emission Trading System (ETS) is the most extensive climate mitigation scheme in Europe, but it is not without limitations. The system requires carbon-intensive EU industries to pay for emitted GHG emissions in order to incentivize emission reduction (European Commission, 2023a, p.3). However, the system has resulted in risk of carbon leakage.

Currently, this risk is managed by granting free allowances to specific industries at high risk. The free allowances are given as a temporary solution to ensure domestic competition with foreign companies. Eventually the free allowances need to be phased out for the EU to reach their climate goals (Regulation 2023/956, §11).

One of the proposals in the "Fit for 55" package is the Carbon Border Adjustment Mechanism (CBAM). The mechanism operates as a carbon tariff on specific sectors to prevent carbon leakage. A carbon tariff implies that companies importing sector specific goods to the EU must pay a tariff that reflects the carbon content of these goods. The CBAM regulation also encourages non-EU industries to reduce emissions (European Commission, 2021, p.3). In May 2023 the CBAM initiative was signed affecting six carbon intensive sectors; aluminium, steel, cement, hydrogen, electricity and fertilizers. CBAM will gradually be required for imported goods into the EU ETS covered region (European Commission, 2023b, p.1). EFTA countries, including Norway, are a part of the EU ETS, but have yet to decide if they want to be included in the CBAM regulation (Gjerstad & Melgård, 2023).

This thesis provides an overview of the EU's policy proposal on implementing CBAM in the EU region and will specifically focus on the nitrogen fertilizer market, which is one of the six carbon intensive sectors covered by the CBAM. Looking into several scenarios, we create an ex ante partial equilibrium model that simulates the effects of a CBAM on European and the global fertilizer market. The paper will answer the following research question:

How effective is the implementation of CBAM on global GHG emission reduction from the global fertilizer industry? And what could be the consequences for the fertilizer industry both in the EU and Norway?

1.1 Outline

Our thesis is structured as follows. Chapter 2 provides background information and an overview of ambitions for climate policy both in the EU and in Norway. The chapter also presents a description of the fertilizer market. In Chapter 3, we will describe relevant theory and literature reviews to understand CBAM. Chapter 4 presents the model and the research data upon which the analysis is constructed. The results of the simulations will be presented in chapter 5, and further discussed in chapter 6. Finally, in chapter 7, the thesis combines the paper's findings in a conclusion.

2. Background

2.1 The European Union’s climate policies

For the EU to be in line with the Paris Agreements objective for climate-neutrality by 2050, the EU has actively updated their climate policy framework. The European Commission (2021) aims at reducing GHG emissions by at least 55% within 2030 compared to levels from 1990. To achieve this objective, the EU Emission Trading System (EU ETS) must be revised. As announced in the European Green Deal, the proposal is to reduce the numbers of quotas and simultaneously phase out free allowances in the EU ETS. Free allowances will be replaced by an initiative for a Carbon Border Adjustment Mechanism (CBAM) (Regulation 2023/956, §12).

2.1.1 The progress of ETS

The Emission Trading System (ETS) is a market-based cost-effective instrument established to reduce GHG emissions within the EU (Ellerman et al., 2016, p.90). Since the launch in 2005, the system has effectively reduced emissions from power, heat and industry sectors by 37,3%. In 2022 most of the revenue generated from the initiative was used to support climate and energy projects, including measures to address the effects of the energy crisis (European Commission, 2023a, p.3 & 15).

The system aims at achieving climate neutrality while ensuring competitiveness for European industries (European Commission, n.d-b). The purpose is to shift the cost burden from GHG emission abatement back to those companies who are responsible for emitting. By internalizing the costs associated with emissions, industries are forced to adopt emission-reducing measures and invest in cleaner technologies, which will enhance social welfare (European Court of Auditors, 2021, p.6-7).

The EU ETS cap sets the maximum allowable volume of emissions for regulated producers within each trading phase, equivalent to the number of allowances distributed. However, the cap is not rigidly fixed; rather, it is designed to evolve over time in response to market dynamics and policy objectives. The quota system is currently in the fourth phase (2021-2030), where the cap reduces annually by 2,2%. This is an increase from the third phase (2013-2020), where the annual reduction was set to 1,74% (Ellerman et al., 2016, p.89-91). Additionally for the third phase, the Market Stability Reserve (MSR), was introduced as part of the EU ETS, which further enhances this adaptability (European Commission, 20203a, p.25). The MSR addresses fluctuations in the carbon market by removing and invalidating surplus allowances. As a result, the availability of long-term supply of emissions permits effectively decline (Rosendahl 2019, p.734). The MSR mechanism therefore promotes market stability within the trading system and ensures a balanced and robust carbon market (European Commission, 2023a, p.26-38).

A downside to the EU ETS is the risk of carbon leakage. Although some individual countries have substantial climate policies, such as the EU, the absence of significant policies from other countries can undermine this effort. That is why carbon emissions are “leaking” out of the climate coalition when abating countries increase their emissions in response to the coalition’s abetment (Lessmann et al., 2015, p.821).

The primary mechanism to limit the risk of carbon leakage is currently the allocation of free allowances. These allocations are granted by the EU to specific industries at high risk of leakage based on sector specific performance and benchmark levels. The distribution of free allowances is described as a transitional measure which eventually will be phased out (European Commission, 2023a, p.13). Free allocation allows the industrial sector to emit without paying for quotas, and consequently prevents shifting production of carbon-intensive products from carbon-constrained countries in the EU to non- or less constrained regions outside the EU (European Commission, 2020, p.13).

Distributing free allocations will not be a sufficient policy instrument in the long run. Meaning free quotas will not create incentive for domestic producers to reduce emissions enough to reach current climate goals. Compared to full auctioning, free allocation weakens the price signal, and reduces incentives for decarbonization investments (European Commission, 2021, p.2-3). Over time, free allowances are therefore gradually replaced by auctioning, which in return increases the risk of carbon leakage. In order to address this increased risk, the revision of the EU ETS therefore introduces CBAM as a new alternative to free allowances. It aims to equalize the playing field for high-emitting industries in the EU, and serves as a safeguard against carbon leakage, while at the same time allowing for a phase out of free allocations (Bellora & Fontagné, 2023, p.1).

2.1.2 The introduction of CBAM

The EU's CBAM functions as a carbon tariff on imports. The general principle of the CBAM is to charge a carbon price on imports to the EU, equivalent to the carbon price paid by domestic producers (Bellora & Fontagné, 2023, p.2). The implementation of CBAM reduces the risk of undermining EU's climate initiatives due to carbon leakage. CBAM also urges non-EU countries to reduce emissions (European Commission, 2023b, p.3).

The CBAM system mirrors the system of allowances in the EU ETS. For instance, the distribution of CBAM will be based on the carbon intensity of the imported goods. EU importers will buy CBAM certificates corresponding to the carbon price that would have been paid, had the goods been produced under the EU's carbon pricing rules. Conversely, if a non-EU producer has already paid a carbon price in a third country on the embedded emissions in the imported goods, the corresponding cost will be fully deducted from the CBAM obligation. The price on certificates will be estimated on a weekly average to reduce uncertainty for the importer in the EU (European Commission, 2021, p.-18).

Under the EU ETS, the cap determines the supply of emissions allowances and provides certainty about maximum GHG emissions. The carbon price is determined by the balance of that supply against the market demand. In contrast, CBAM regulation does not impose a cap on the number of CBAM certificates available to importers. This is to avoid restriction in trade flows (European Commission, 2021, p.18). Additionally, the proposed CBAM aligns with the EU's international commitments, including the World Trade Organization (WTO) rules (European Commission, 2024, p.8). For a carbon tariff to be compatible with WTO it follows the principles of non-discrimination under the General Agreement on Tariffs and Trade (GATT). These principles include the most favored nation principle (MFN), GATT Article I, and national treatment (NT), GATT Article III. Which dictates conditions for countervailing measures on imports (Böhringer et al., 2022, p.23).

At first, CBAM will apply to selected industries and imports of certain goods with high GHG emission intensity, and at most significant risk of carbon leakage. These specific imports are cement, iron and steel, aluminum, fertilizers, electricity and hydrogen (Regulation 2023/956, §31-32). When fully phased in, CBAM will cover more than 50% of the emissions in ETS covered sectors (European Commission, 2024, p.9-10). CBAM will be introduced in the market gradually, with a transitional period from 1st of October 2023 to 31st of December 2025. During this period, the six selected industries will only have to monitor and report embedded GHG emissions on imported goods and are not yet required to pay the CBAM certificates. Thus, ensuring a careful and foreseeable implementation for public authorities as well as industries in and outside the EU (European Commission, 2023b, p.3).

A shared central platform will be used by member states to sell CBAM certificates to authorized CBAM paying importers (European Commission, 2024, p.38). A review of the CBAM's functioning during the transitional phase will be concluded before the entry into force of the definitive system. Simultaneously, the scope of CBAM is expected to extend to other carbon leakage exposed goods and sectors covered by the EU ETS (European Commission, 2024, p.40).

The EU will also continuously review the extension of CBAM to not only include direct emissions but also explore the inclusion of indirect emissions (Regulation 2023/956, §65). The CBAM proposal currently disregards indirect emissions from electricity production because of legal concerns on whether including the indirect emissions mirror the ETS system. Currently, EU members may grant compensation to mitigate the impact of increased electricity prices on electricity intensive sectors which is one of the reasons why the indirect CBAM emissions are omitted. This is because the compensation mechanism would put the electricity sector in the EU at a disadvantage compared to foreign industry, if the CBAM were to include indirect emissions for these sectors. The fertilizer and cement sector are exempt from the policy and are therefore currently the only sectors required to pay CBAM costs on indirect emissions from electricity (Ling et al., 2024).

Norway, and the other European Economic Area (EEA) countries are today a part of the ETS, but not CBAM. The decision of whether or not the countries will include CBAM within national law is however yet to be decided. Norway states that the CBAM is of non-EEA relevance and are therefore not obliged by law to implement the system. In contrast, the EU holds the perspective that the CBAM is indeed of EEA relevance. Norway is currently in dialogue with the European Commission and the other EEA countries on their potential implementation of CBAM (Gjerstad & Melgård, 2023).

2. 2 The fertilizer industry under CBAM

One of the six carbon intensive sectors covered by the CBAM is the fertilizer industry (European Commission, 2024, p.9). Manufacturing of Nitrogen fertilizers is listed on the European Commission's list of sectors at risk of carbon leakage (Commission Delegated Decision 2019/708, Annex 1). Fertilizer Europe argues that nitrogen fertilizer poses a significant risk of carbon leakage, due to its emission intensive production and high trade exposure (Fertilizers Europe, 2022a, p. 15). Nitrogen fertilizers, mixed fertilizers that include nitrogen as well as ammonia and nitric acid, used in production of nitrogen fertilizers, are the commodities covered under the CBAM regulation (Regulation 2023/956, Annex 1 §2).

2. 2. 1 The Fertilizer Market

The price of nitrogen fertilizer depends on demand and supply as well as geopolitical conditions. The demand for fertilizer is dependent on the global food demand, crop prices and ability to pay, while supply is dependent on the availability of raw materials and input costs for producers (Cross, 2023, p. 2). Nitrogen fertilizer is the most important input in crop production, making the elasticity of demand for nitrogen fertilizer inelastic (Matthews, 2022, p. 39). According to a Danish study, price elasticity of demand ranges from -0,24 to -0,69 (Hansen, 2004, p. 14). When considering supply of nitrogen fertilizers, natural gas prices account for 60-80 % of production costs (Fertilizers Europe, 2023c), which is why shocks in gas prices have consequences for fertilizer supply. Due to inelastic fertilizer demand, natural gas prices also affect crop prices. Given the inelasticity of demand, and fertilizer production`s dependence on fossil fuel, the fertilizer price is sensitive to geopolitics (Schnitkey et al., 2023, p. 4).

Russia and China are the two largest nitrogen fertilizer exporters in the world (FAO, 2024), but are also countries associated with political instability. As a result of the war in Ukraine, as well as export restrictions in China, there has been shortages and increased fertilizer prices (Broom, 2023). Due to fertilizers' importance for food production, political instability can therefore cause risk for food security. To ensure food security, Europe has built 120 fertilizer sites located within the European continent (Ausfelder et al., 2022, p. 11). Despite the large production, the EU is still a net importer of nitrogen fertilizers (FAO, 2024), with one third of the imports still coming from Russia (Mambro, 2024). Norway also imports to the EU, but is compared to Russia a less significant importer (FAO, 2024).

The demand for fertilizers varies across the world, depending on the farmers ability to pay as well as the nutrient condition in the soil. For instance, is the usage of phosphorus and potassium fertilizer more common in Brazil, and in China, than in other parts of the world. Nitrogen fertilizers are the most used mineral fertilizer per hectare of cropland, and the usage is much smaller in poor regions, such as Sub-Saharan Africa, where the ability to pay is low (Ritchie, 2021). In Europe consumption of fertilizers is high, especially for nitrogen fertilizers. In 2021, the usage of nitrogen fertilizers in EU agriculture was equivalent to 90% of the mineral fertilizer market in the EU (Eurostat, 2023).

Due to energy efficiency technology, the demand for nitrogen fertilizers in the EU is expected to decrease by 4% from 2021 to 2031 (Fertilizers Europe, 2022b, p. 4-12). Despite the expected decrease of the EU fertilizer market, there is a projected increase in demand for low carbon ammonia, a vital component in nitrogen fertilizer production. The demand for ammonia is expected to triple due to new uses for ammonia, such as in the maritime sector. This effect is however expected to be long term, and it is projected that the largest increase in market size will occur after 2030. It is nevertheless likely that the fertilizer market will experience significant changes to come (Zeeuw, 2024).

2.2.2 Production of Nitrogen Fertilizers

When looking into emissions from nitrogen fertilizers, it is important to distinguish between emissions from the production processes, and emissions from usage. According to the International Fertilizer Association (IFA) fertilizers represent 2,5% of the global GHG emissions, including 1% from production. The remaining emission comes from released N_2O emissions from the soil in fertilizer application at the farm (IFA, 2019, p. 2-3). Although large parts of emission from fertilizers come from usage, only emission from production processes is covered by the CBAM, including indirect emissions from electricity generation (European Commission, 2024, p. 19).

Ammonia is an important component in nitrogen fertilizer production, and is today most commonly produced by a technology called the Haber-Bosch process, illustrated in figure 1. In the process nitrogen from the air is combined with hydrogen from natural gas by a steamer to produce ammonia, releasing GHG emissions as byproduct (Fertilizers Europe, 2023a). Fertilizer Europe argues that European fertilizer has a 50% smaller climate footprint than global average, (Fertilizers Europe, 2022a, p. 16) but still generates a large amount of GHG emissions (Fertilizers Europe, 2023b). Chinese coal-based nitrogen fertilizers, using coal as input for ammonia production, are considered to produce the most emission intensive fertilizers globally (Wendołowski, 2019, p. 12).

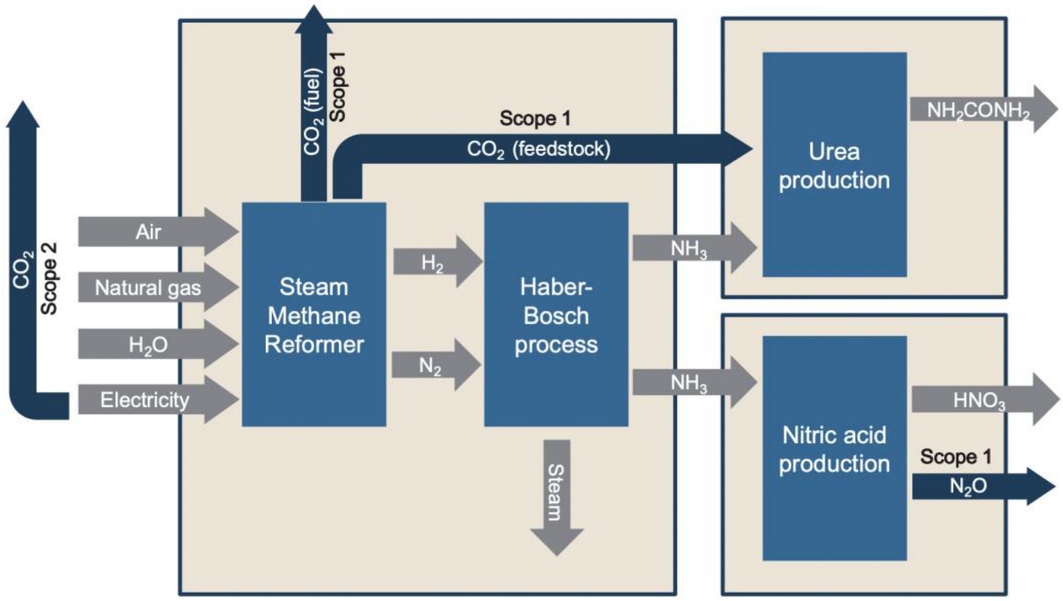

Figure 1: Production of nitrogen fertilizers using gray hydrogen in the Haber-Bosch process (Ausfelder et al., 2022, p.16).

2.2.3 Potential for further emission reduction in EU and Norway

The EU has decreased direct emissions from production, and emissions from indirect electricity in fertilizer production by 49% between 2005 and 2020 (Fertilizers Europe, 2023a). This reduction was realized through energy efficiency improvements in EU power plants as well as the usage of abatement technology in nitric acid production (Wendołowski, 2019, p. 12). However, according to the industry, European fertilizer production has already reached its limit on emission reduction using today's methods. Further investments in mitigation initiatives with current technology will therefore have little effect on GHG emissions. In order to reach commitment to climate neutrality, the European fertilizer industry would therefore have to undertake large investments in new technology (Fertilizers Europe, 2023a).

There are mainly two potential pathways for emission reduction in European fertilizer plants. The first pathway, named the Green Hydrogen Pathway, requires ammonia to be produced by alternative renewable sources for hydrogen production. The other alternative is called Technology Neutral Pathway, which is the Carbon Capture and Storage technology (CCS) used as means to remove the direct emissions from the natural gas-based ammonia production. Both these technologies require large investments, infrastructure improvements and climate policy which incentivizes these initiatives (Fertilizers Europe, 2023a).

In combination with CBAM, the EU has decided on a second initiative to speed up reduction of carbon emissions from the fertilizer industry, as well as other industries transitioning from gray to green hydrogen. In the revised Renewable Energy Directive (RED III), 42% of hydrogen used in EU industry is required to be produced from renewable sources by 2030 (Erbach & Svensson, 2023, p. 6).

RED III is currently under revision by the Norwegian parliament, and it is not yet decided if the legislation will be included in Norwegian law (Regjeringen, 2023). The decision to reach 42% renewable hydrogen is ambitious and would include large investment costs and massive production of renewable energy. According to a German outlook for 2030, on-site production cost of ammonia in the EU, using green hydrogen, varies from 760-1350 €/ t NH_3, depending on the geographical location of the power plant (Ausfelder et al., 2022, p. 9).

It is projected cheaper to build green hydrogen in Northern Europe than the rest of the continent, making future Norwegian green ammonia production relatively attractive (Ausfelder et al., 2022, p. 9). Norway is currently building a pilot project at the country's largest fertilizer factory at Porsgrunn. The project is expected to be finalized in 5-7 years and result in the production of 400 000 tonnes green ammonia. Despite this advantage, Norway's on-going green hydrogen project at Porsgrunn is facing difficulties. Although Yara has been granted grid capacity needed to realize yearly electricity demand of 4 TWh, the required grid does not exist today. In order to execute demand for 4 TWh, Statnett, being the country's Transmission System Operator, must accelerate grid capacity to a whole new pace (Moestue, 2023). Both cost parameters, as well as the favorable infrastructure changes, are needed for the future decarbonization of the industry.

2.2.4 The European industry`s reaction to CBAM

Because of the European fertilizer industry's exposure to carbon leakage and lack of competitiveness to foreign suppliers, the industry receives free allowances for emissions under ETS. In 2021 European ammonia fertilizer producers received 78% of their total required emission allowances for free (Fertilizers Europe, 2022a, p.14). The value of free allowances is calculated based on a benchmark set to the average 10% best performing products, where free allowances for the fertilizer industry were set to 100% of the benchmark (European Commission, n.d-a). This means that the 10% best performing producers receive all of their allowances for free. Since some producers have larger emissions than the benchmark, they are still required to pay the difference between the benchmark and actual emissions. By 2030 free allowances for carbon intensive industry will be reduced to 51,5%, in order to ensure a further shift towards renewable technology solutions (Directive 2023/959, §46).

Although the European fertilizer industry has expressed support for the EU`s CBAM, they are also concerned for the manner in which the policy is designed. The CBAM will help the domestic industry compete with the foreign suppliers within the EU, but overlooks the disadvantage European exporters may face in international markets. Although the EU is a net importer of nitrogen fertilizer, they still have some export on specific fertilizer products. Fertilizers Europe urges the EU to change its design, and include support for export in its policy so that the industry also remain competitive abroad (Fertilizers Europe, 2023d). The problematics surrounding the request will be further described in section 3.5.

The combination of high gas prices, increased ETS prices and RED III creates increased costs for nitrogen fertilizer production in the EU. The difficult conditions result in an increased risk of outsourcing part of the industry, and EU producers looking at alternative locations for fertilizer production. Biden's Inflation Reduction Act (IRA), provides significant subsidies for green hydrogen production, making the United States an attractive alternative location for hydrogen decarbonization investments. The potential reallocation of parts of the EU nitrogen fertilizer production remains unclear at current date (Zeeuw, 2024).

3. Theory & Literature Review

This part of the paper consists of various literature and theoretical frameworks for understanding the components of ETS and CBAM. Firstly, we will explain the theoretical framework of trade and climate economics. Secondly, we will provide a literature review of the CBAM design and expected effects of implementing the mechanism in combination with free allowances phase-out.

3.1 Trade and market equilibrium

Adam Smith claimed in his work in *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776), that free trade results in an outcome which is good for the whole society despite individual selfishness. Today, Smith's statement, describing the free-market theories of economics, stands at the very center of western economic thinking (Buchanan, 2002).

International trade is a fundamental concept in economics that refers to the exchange of goods and services between countries. At its core, trade facilitates the efficient allocation of resources and promotes economic growth by allowing entities to specialize in the production of goods and services in which they have a comparative advantage. This kind of advantage is the ability to perform an activity or produce a resource at a lower opportunity cost than others. Thus, international trade fosters economic interdependence and globalization (Bade & Parkin, 2011, p.216). Despite the advantage of international trade, governments use different policies to influence trade and protect domestic industries from foreign competition. These policies include tariffs and import quotas, which influence the flow of resources across borders. Tariffs are taxes imposed on imported goods, while import quotas restrict the quantity of specific goods that can be imported. These policies aim to protect domestic industries and regulate trade flows (Bade & Parkin, 2011, p.225 & 229).

To comprehend the dynamics of international trade and trade imbalances, it is imperative to explain the mechanisms through which the global market adjusts. A market serves as a platform facilitating transactions between buyers and sellers, where information is distributed, and business transactions are conducted (Bade & Parkin, 2011, p.48). In many economic models there exists an assumption of perfect competition as a market structure.

Alfred Marshall defined a perfectly competitive equilibrium as the state a market would be in if all decision-making entities, and companies in particular, were devoid of market power. A market is perfectly competitive when agents are maximizers, where producers transform inputs into output which maximize economic profit within cost constraints. Consumers who buy the outputs aim to maximize their utility function within their income constraints. Agents' decisions in the market are independent of each other, meaning there are no coalitions or collusion, and production and consumption decisions do not create external effects. Moreover, the market consists of many buyers and sellers of homogeneous goods, so that no one is able to exert a significant influence on the market quantities. The level of competition within the market is gauged by the number of participants in each given sector, resulting in agents being price-takers. Additionally, both producers and consumers possess complete information regarding production and consumption possibilities, eliminating uncertainties and information asymmetries among agents (Becchetti et al., 2020, p.141).

These criteria enable the determination of optimal production quantity that maximizes the net benefits, which equals the difference between total benefits and total production costs, shown in figure 2. Because the price is determined by the market under perfect competition, the price equals marginal revenue, and the optimal quantity is where the price equals marginal cost. When production reaches this point (MR=MC) agents will be indifferent, as they neither take loss nor profit for the last unit sold (Becchetti et al., 2020, p.142-144).

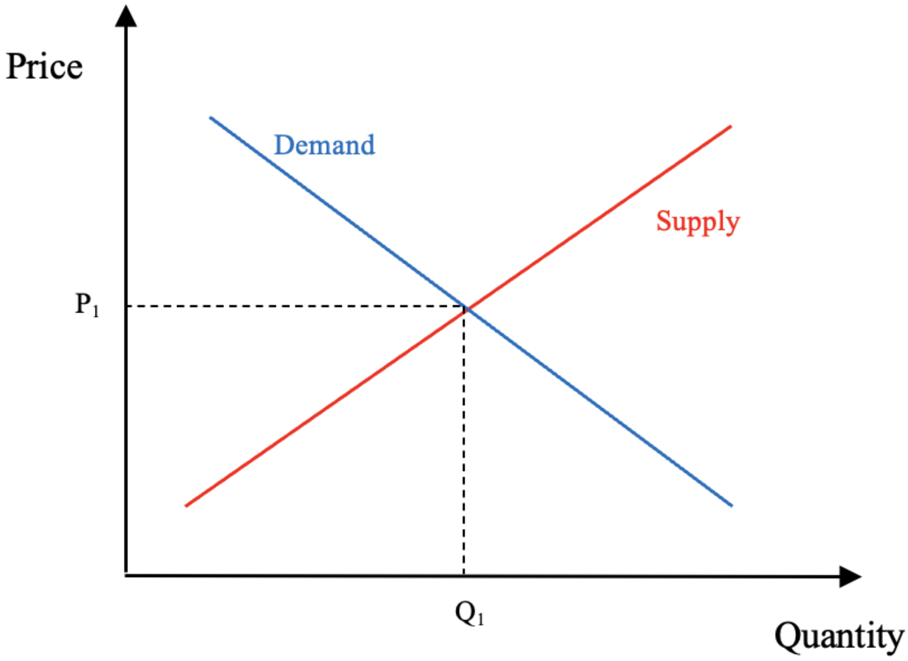

Figure 2: Equilibrium in a perfectly competitive market.

The demand curve reflects the collective marginal willingness to pay within the market, and the slope is affected by price elasticity (Bade & Parkin, 2011, p.114). Price elasticity of demand varies across different goods and can therefore impact the market differently. For instance, goods with elastic demand experience more significant changes in quantity demanded in response to price fluctuations, while goods with inelastic demand are less sensitive to price changes. Inelastic goods are necessity goods which we cannot live without (Andresen, 2021). The impact of a tariff on demand therefore depends on the necessity of the specific good and its demand elasticity.

3.2 Carbon pricing

Climate change poses an alarming threat to the global environment and economy. The accumulation of GHG emission over time leads to long-term climate disruptions. Climate change can therefore be described as a “stock pollution” problem emphasizing the necessity for sustained effort to mitigate emissions continually (Perman et al., 2011, p.143-144).

Businesses frequently overlook the social costs associated with emissions from their production, as they lack the incentive to consider such external costs. Thus, neglecting the adverse effects of the Social Cost of Carbon (SSC). SCC is the economic costs associated with damages from increased CO_2 emissions. These damages include changes in agriculture, flood risk, ecosystem services, and other effects on social welfare (Greenstone et al., 2013, p. 23-24). Because the SCC is not properly accounted for by businesses, the price of carbon intensive goods is inaccurate. To rectify this imbalance, the implementation of a pricing mechanism for emissions, guided by the "polluter pays principle", is advocated. By internalizing the costs associated with emissions, this principle ensures that emitters bear the financial burden proportional to their environmental impact. Putting a price on GHG emissions is a way of making the polluters pay for emissions. Consequently, companies are incentivized to adopt emission-reducing measures and invest in cleaner technologies, aligning their economic activities with environmental sustainability objectives and enhancing social welfare (European Court of Auditors, 2021, p.6-7).

Since GHG emissions have a global impact, mitigation efforts yield the same benefits regardless of their location. Mitigation efforts can therefore be considered a global public good, as everyone has access to its benefits (Michaelowa, 2015, p.397). This makes “free-riding” a valid concern when developing international climate policies such as an international carbon price. Free-riding happens when someone enjoys the advantages of a public good while avoiding to contribute with the associated costs. In international climate policies countries have an incentive to rely on the emissions reductions of others without contributing with domestic abatement (Nordhaus, 2015, p.1339). However, countries can achieve more social welfare if they maintain collective action and cooperation. Nations therefore have reasons to establish institutions that promote emission reductions while discouraging free-riding. These institutions are called International Environmental Agreements (IEAs) (Barrett, 1994, p. 878). The Paris Agreement and the Kyoto Protocol are examples of IEAs.

3.3 The EU ETS

The Emissions Trading System (ETS) of the EU is the world's most extensive cap-and trade system (Ellerman et al., 2016, p.89). The ETS puts a cap on emissions, requiring the energy, aviation and industrial sectors in Europe to pay for aggregated emissions (European Commission, 2023a, p.3).

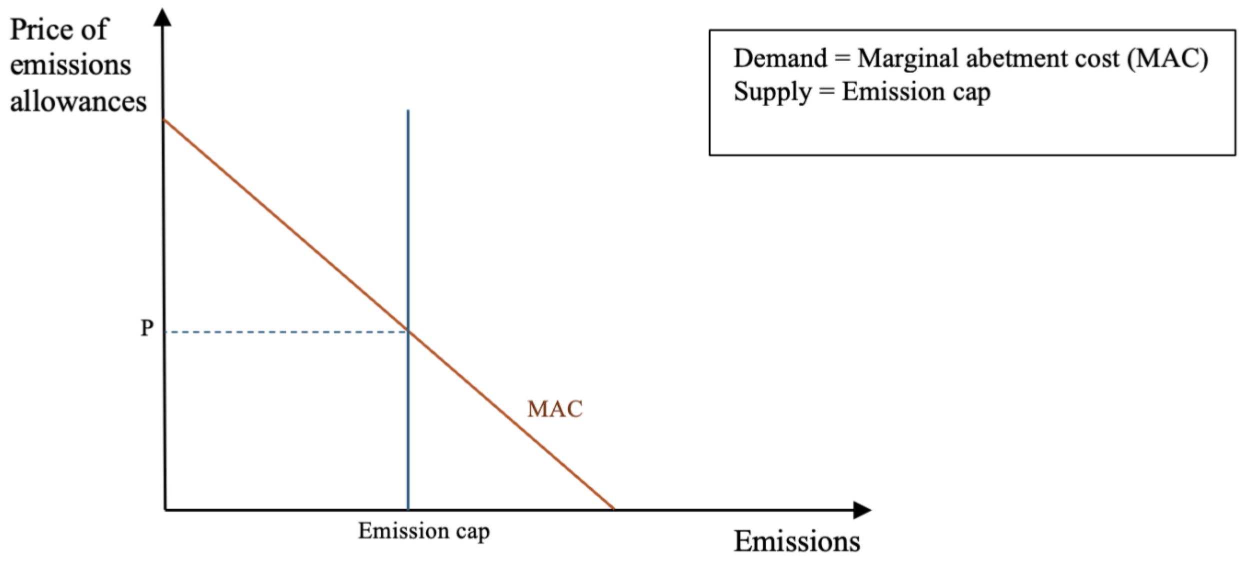

Figure 3: An illustration of static ETS market (K. E. Rosendahl, Lecture 6, 2022).

This figure illustrates a static quota market where total emissions in all sectors are regulated by ETS, without the possibility of saving quotas. The supply of quotas is constant and given by the emission cap for the period, which forms a vertical supply curve. Since total emissions covered by the system cannot be higher than this cap the supply of emission allowances is fixed. The demand for emissions is represented by the Marginal Abatement Cost-curve (MAC). The MAC-curve is defined as the producer's cost of reducing one additional unit of GHG emissions (Kesicki & Stracham, 2011, p.1195). The price can be found in figure 3, where the cap and the MAC-curve cross. In this quota market, the emission quantity remains constant, while the price is endogenous and fluctuates depending on the MAC-curve. As prices increase more producers will prefer to reduce emissions instead of paying for the emission allowances. Therefore, the demand for emission allowances depends on the cost of reducing emissions as well as the number of available allowances in the market (the cap).

The EU ETS is characterized as a cost-effective policy aimed at reducing emissions while maximizing economic efficiency. By allowing polluters to trade emission allowances, the ETS ensures that emissions are reduced at the lowest possible cost. In a perfectly competitive market, as explained in chapter 3.1, the marginal cost of reducing each additional unit of emissions is equalized, leading to the minimization of total costs in achieving environmental targets. In turn, this system of carbon pricing generates revenue, which can be directed towards investments in climate mitigation measures and further development of green technology (European Commission, 2023a, p.3 & 15).

One of the central aspects of the EU ETS is the distribution of allowances, which are essentially permits that allow entities to emit a certain amount of GHG annually. The allowances can be auctioned out by the government or distributed for free according to specific criteria. For instant sectors with high risk of carbon leakage receive free allocations, as mentioned in subchapter 2.1.1. The number of free allowances allocated to companies is calculated based on sector specific benchmark values for particular products. These benchmarks are standards for emissions intensity (European Commission, 2023a, p.14). Firms that emit less than the benchmark receive surplus allowances that they can sell, while those emitting more must purchase additional allowances. As described in section 2.2.4, the benchmarks are determined by the sector specific 10% best performing products in each sector (Ellerman et al., 2016, p.93). Highly carbon leakage exposed sectors, like the fertilizer industry, are placed on the carbon leakage list and will receive allowances equivalent to 100% of the relevant benchmark for free (European Commission, 2023a, p.13-14).

3.4 Carbon leakage

To cut emissions where abetment is most affordable, there is need for a global coordinated price on carbon. A global cost-effective system would have been possible if all countries were subject to a functioning IEA with a common system for carbon pricing, either through coordinated emission taxes or interconnected ETS. However, global carbon pricing and coordinated climate policies, while ideal, is not realistically achievable (Böhringer et al., 2022, p.22).

The present situation involves separate carbon pricing systems that are not connected to each other and only cover limited geographic areas. These scattered systems result in spillover effects of emissions in other regions, undermining global emission reduction efforts. This phenomenon is called “carbon leakage” (Böhringer et al., 2022, p.22). Bosch et al. (2007) define carbon leakage as:

$$\frac{Emission\ increase\ outside\ regulated\ region}{Emission\ reduction\ in\ regulated\ region}$$

The formula measures carbon leakage as the ratio between changes in emissions within and outside the regulated region. If the entire emission reduction is offset by an increase elsewhere, there exists 100% carbon leakage (Bosch et al., 2007, p.665). As climate change depends on global emissions, carbon leakage threatens to reverse the effects of individual policy efforts (Naegele & Zaklan, 2019, p.126).

Carbon leakage mainly arises from two primary channels: the competitiveness and the international fossil fuel channel. Leakage through the competitiveness channel occurs when countries that implement emissions reduction measures face higher emission reduction costs in comparison with countries who have less significant commitments. Consequently, their goods become more expensive than those from unregulated regions which initially results in reduced exports and increased imports from regions not facing the same carbon costs. Over time, this imbalance prompts a shift in investment and production towards these unregulated regions, which in return also causes emission to relocate to these regions (Zhang, 2012, p.228).

Leakage from the fossil fuel channel occurs in an open economy when fossil fuel demand reduces because of regional restrictive fossil fuel policies. When fossil fuel demand in carbon restricted regions decreases, it can cause a reduction in global fossil fuel prices. Thus, stimulating increase in demand for fossil fuels in unregulated regions, causing these regions to emit more. According to studies, the fossil fuel channel is found to have the largest effect on carbon leakage (Zhang, 2012, p. 228). Böhringer et al. (2010) found that since most of the leakage come from the fossil fuel channel, the EU cannot reduce carbon leakage more than 33% when implementing policy to cut emissions by 20%, compared to a scenario with full permits auctioning (Böhringer et al., 2010, p.22). Carbon leakage through the fossil fuel channel is therefore important to address when implementing carbon restrictive policy (Zhang, 2012, p. 228).

In order to avoid putting industries exposed to a risk of carbon leakage at a competitive disadvantage, governments or unions can implement carbon leakage reduction measures. Free output-based allocation (OBA) and Border Carbon Adjustment (BCA) are examples of such policies, further explained in the next paragraphs. The policies differ in their effectiveness at preventing carbon leakage and shielding domestic industries from exposure. Research has found that although both measures are effective for protecting domestic production, the policies do not have the same effect on preventing carbon leakage (Zhang, 2012, p.258-259).

BCA is effectively a carbon tariff, on imported carbon intensive goods. Similar to section 2.1.2 on EU's CBAM, the BCA imposes a cost on the carbon emissions embedded in imported products from regions without carbon pricing systems. The difference between the BCA and the EU's CBAM is that the CBAM is specifically designed to meet EU obligations, while the BCA is a commonly used umbrella term in research on carbon tariffs (Carbon credits, 2022). BCA helps reduce leakage through the competitiveness channel. Also, by sharing the cost of carbon pricing through trade, BCA can improve global cost-effectiveness. Despite the perks of BCA, legal and practical constraints on implementations can reduce the effectiveness of the policy (Böhringer et al., 2022, p.22). Further limitations of the BCA will be addressed in section 3.5.

OBA, or OBR (Output-Based Rabets) is a mechanism that tailors firms amount of free emission permits to the level of production output rather than imposing fixed caps (Zhang, 2012, p.255). Because the EU's allocation of free allowances is partly based on outputs, as accounted for in section 2.1.1, it functions similarly to OBA. Firms can still reduce their carbon costs by reducing emissions but are exempted from the full costs for the remaining embodied emissions. OBR dynamically adjusts free emission allowances in proportion to the level of output, thereby reducing the risk of leakage by encouraging firms to improve efficiency and reduce emission intensity while maintaining competitiveness (Böhringer et al., 2022, p.27). Despite the advantages of OBA, The European Commission expresses how distributing free allocations will not be a sufficient policy instrument in the long run to reduce the risk of carbon leakage. Compared to full auctioning, such free allocation weakens the price signal that the system provides and thus affects the incentives for investment into further reducing GHG emissions, as clarified in subchapter 2.1.1.

3.5 Carbon Border Adjustment Mechanism (CBAM)

This subchapter is a literature review of the design and possible market impacts of the Carbon Border Adjustment Mechanism (CBAM). The different results from previous studies are more generally applied to implementation of BCA, a foundation from which the EU's CBAM is derived. This assumption is based on BCA being a tariff on imported goods proportional to embodied carbon and to the CO_2 price, as explained in 3.4. In addition, a few studies in this subchapter interpret the possible effects of CBAM with current EU design.

3.5.1 CBAM Design

The EU aims to introduce CBAM in the international trade market, as outlined in section 2.1.2. The primary purpose is to reduce the risk of carbon leakage, safeguard domestic competitiveness, and foster global climate cooperation.

The EU's CBAM design, as mentioned in chapter 2.1.2, includes direct emissions from production processes, as well as indirect emissions from electricity production for the cement and fertilizer industry. The direct emissions are those that physically occur at the production site. Indirect emissions include emissions that occur outside the area of production

(Bjørklund, 2021). Thus, when CBAM is implemented, the design will specifically address direct emissions and indirect emissions for the fertilizer sector.

Domestic indirect emissions play a significant role in embedded emissions and contribute to variations in emissions intensities across regions. Böhringer et al. (2022) studies the potential effects of implementing a BCA dependent on its condition and design. The study evaluates the effect of including direct and indirect emissions for BCA. Among many findings, they found that relying solely on direct emissions would underestimate the total emissions included in carbon-intensive goods (Böhringer et al., 2022, p. 22 & 24). Furthermore, the study underscores the need for careful consideration when implementing a carbon tariff. While incorporating both types of emissions can be practically challenging, it can give a more accurate measure of the carbon content used in production (Böhringer et al., 2022, p. 23 & 25).

Another aspect when looking at CBAM design, is to secure compatibility with WTO's international trade regulation. These regulations dictate conditions for countervailing measures on imports, as explained in subchapter 2.1.2. WTO rules prohibit certain types of subsidies that are considered to distort the flow of trade. This means that a BCA is more likely to comply with regulations if the restrictions mirror policy within the carbon restricted region (Böhringer et al., 2022, p.23).

In addition to WTO regulations, there exists a probability for international trade tension when implementing a carbon tariff. Countries such as China and Japan can perceive the tariff as an unfair protectionist trade policy, which in the worst case could trigger a future trade conflict. This is because countries impacted by the effect of CBAM may retaliate with their own versions of trade barriers or tariffs in response, escalating tensions between trading partners (Bergin et al., 2021, p.4-5). In addition, Böhringer et al. (2022) point out that creating a carbon tariff to safeguard domestic competitiveness, rather than solely for leakage prevention, could violate principles of fairness in international climate agreements. Meaning it could lead to countries reducing their mitigation commitments under agreements like the

Paris Agreement, further exacerbating tensions and undermining the effectiveness of a carbon tariff (Böhringer et al., 2022, p.27).

3.5.2 Expected effects of CBAM

Based on a literature review, we will examine how a carbon tariff is expected to impact the fertilizer sector. Since BCA is yet to be implemented the research highlighted in this section is based on ex ante simulations. The results of the studies vary depending on design and scope.

Research by Böhringer et al. (2022 & 2021) and Bellora & Fontagné (2023) indicates that carbon tariffs can effectively reduce carbon leakage and enhance the effectiveness of climate policies, depending on their design. For instance, Böhringer et al. (2021) demonstrate in their static Computable General Equilibrium (CGE) model using WIOD data covering the global economy, that carbon tariffs can lead to a leakage reduction ranging from 64% to 80% (Böhringer et al., 2021, p.673).

Furthermore, Bellora & Fontagné (2023) compared the effects of CBAM with free allowances, and found that CBAM is more effective in reducing carbon leakage than the current free allowances in the EU ETS. Depending on the design of CBAM, the carbon tariff reduces leakage by 34% to 42% compared to free allowances (Bellora & Fontagné, 2023, p.9). They further argue that without CBAM, the increasing cost of allowances from stricter emission constraints would primarily occur for the electricity sector. The CBAM initiative phases out free allowances, ensuring that ETS sectors contribute to emission reductions (Bellora & Fontagné, 2023, p.13-15).

Other studies, on the other hand, have found that CBAM only offers modest protection for domestic competitiveness and global climate cooperation. According to Lestan et al. (2023), while CBAM may offer some benefits in mitigating climate change, it also poses substantial risks to trade flows, competitiveness, and economic growth in regions that rely heavily on exports. This is because implementing sustainable solutions can require significant investments, and these costs will need to be covered by countries impacted by CBAM (Lestan et al, 2023, p.12). Another notable criticism is from Jousseaume et al. (2021) study, who describe the CBAM initiative as "damaging to both climate protection and EU export industries". The underlying issue is that CBAM primarily shields domestic EU producers from the risk of carbon leakage but does not affect the competitiveness of EU producers who export their products to other markets (Jousseaume et al., 2021, p.5). Additionally, CBAM does incur costs, shown in increased prices of ETS allowances, as compared to free allowances, and thus elevating costs for ETS-related goods, which will be further illustrated in figure 5.

A possible response to these objections is to introduce rebates on exports in the CBAM design. Export rebates are described as a trade policy instrument, to help boost exports of goods. Essentially it means that exporters are compensated or subsidized for the domestic taxation, such as the carbon tax, and can help make the goods more competitive in international markets (Chen, 2006, p.227). Böhringer et al. (2022) suggests that including export rebates from a carbon tariff can increase its effectiveness. However, rebates tend to fail to address the risk of carbon leakage, associated with the loss of market share for carbon intensive trade exposed industries in international markets. While export rebates can help domestic ETS-regulated industries compete in foreign markets, they also pose legal risks and can be seen as unfair trade practices under WTO rules, as explained above in 3.5.1. Export rebates, especially for ETS-regulated firms, could therefore be considered as illegal subsidies (Böhringer et al., 2022, p.23). In addition, Bellora & Fontagné (2023) found in their study that to secure compatibility with WTO's regulation by avoiding export rebates, CBAM would consequently have a weaker effect in reducing the risk of carbon leakage (Bellora & Fontagné, 2023, p.3 & 15). Thus, a dilemma arises between CBAM effectiveness and its compliance with WTO rules.

These studies highlight that while CBAM aims to enhance international climate goals, it can also introduce legal and political challenges. Lanzi et al. (2013) point out that countries pursuing ambitious mitigation policies face issues with carbon leakage and competitiveness (Lanzi et al., 2013, p.3). Thus, while CBAM has the potential to be an effective climate policy, its complex nature requires careful planning and monitoring to prevent design flaws and potential trade conflicts.

3.5.2.1 Market equilibrium effects

Putting the complexity of CBAM design and politics aside, the simple economic effect of reducing free allowances and implementing the CBAM can be illustrated in a market equilibrium model. Both CBAM and ETS cause supply functions to shift in the EU market. Figure 4 and 5 illustrate how the two policies affect both price and produced quantity in the market.

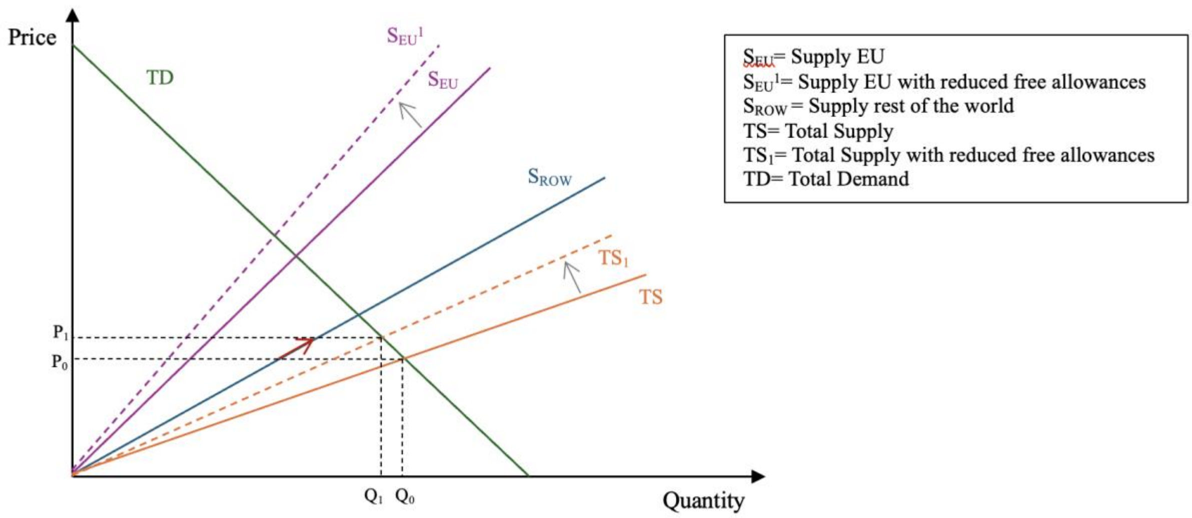

Figure 4: The market effect of reducing free allowances in the EU.

In figure 4, a simplified EU market is depicted where the supply consists of European production (S_{EU}) and production from the rest of the world (S_{ROW}) imported into the EU. The total supply is represented by the TS-curve, while the TD-curve shows the total demand in the European market. The market equilibrium can be found in the intersection point of these two curves, where price is P_0 and the production volume is Q_0.

The EU`s supply curve (S_{EU}) includes ETS costs as a policy measure with free allowances. When the amount of free allowance available in the EU market reduces as a result of a stricter climate policy, there is a short run decline in EU supply. This effect is a result of increased production costs, represented by a shift from S_{EU} to S_{EU}^1. The out-phasing of free allowances causes reduced production for the EU, and therefore a total drop in supply from TS to TS_1. The demand curve is held constant, while the reduced production volume (Q_1) pushes the market price from P_0 to P_1. The ROW supply curve is unchanged because the EU ETS does not affect the supply for non-EU countries. This market effect puts ROW producers at an advantage to sell in this EU market. They replace EU producers' market share and increase the market price, visualized by a red arrow in the figure above. Consequently, this leads to an increasing rate of carbon leakage, as explained in chapter 3.4.

Moreover, this market shock places EU producers in a position where some producers may have an incentive to reduce GHG emissions from production. How they achieve this depends on the company's MAC, which is previously defined in subchapter 3.3. In the long run, producers will choose to abate emissions as long as MAC is lower than the quota price. When MAC is higher than the ETS price, the industry would prefer to purchase ETS quotas, because reducing emissions is more expensive than paying for quotas. Reducing emissions may take time and large investments depending on the industry. EU suppliers may therefore not have the opportunity to reduce emissions in the short run and would have to buy allowances to maintain production. When abatement technologies are available in the long run, emission abatement may be realized.

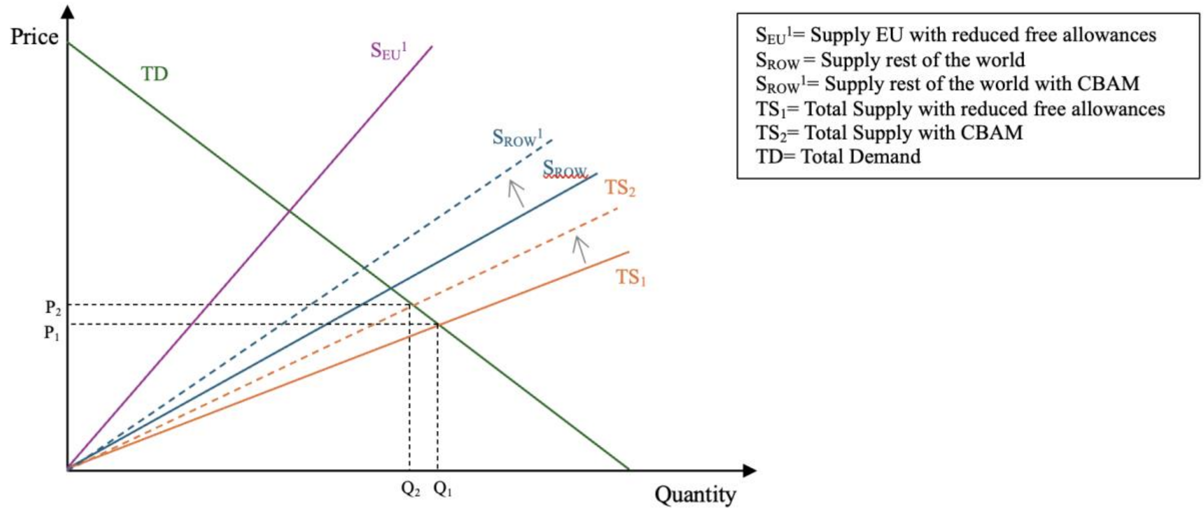

Figure 5: The market effect of introducing a carbon tariff on EU imports.

Figure 5 illustrates the same market as figure 4 with the introduction of a CBAM on ROW imports to the EU. Where the price P_1 and the production volume is Q_1, is equal to the adjustment done in figure 4, for reducing free allowances in the EU ETS. The market shift in this figure demonstrates the introduction of a carbon tariff. Assuming the tariff is paid by the importer into the EU, this leads to higher costs and thus a shift in the foreign supply curve (S_{ROW}^1). The carbon tariff is assumed to roughly equalize the production costs between the two regions. As a result, the price increases from P_1 to P_2, and the total quantity decreases from Q_1 to Q_2. European production will increase, while foreign production decreases due to the rise in costs.

The effect of a carbon tariff on price, production output and distribution vary based on how sensitive supply and demand are to price changes. A high rate of price sensitivity will result in a larger shift in the distribution of production output. If the carbon content in EU imports is higher than in EU production, the new distribution will lead to a reduction in total emissions. If imports have a low carbon content, the carbon tariff will be marginal, which will result in no significant changes in production distribution. The combination of the two models, reducing free allowances and phasing in CBAM, shows opposing market effects. As observed the market share for the EU is reduced in figure 4, and in figure 5 it is reduced for ROW suppliers. Consequently, the net effect of combining the two policies becomes unclear. However, the effects on both price and total consumption are shifting in the same direction, leaving a higher price and lower consumption.

3.5.2.2 CBAM on the agriculture sector

The effects of CBAM on the fertilizer sector as demonstrated in figure 5 is supported by literature. A study on how CBAM may affect the agriculture industry by Nordin et al. (2019) shows concerns regarding climate action within the EU, causing carbon leakage abroad and reducing competitiveness in the EU agriculture market. The paper adds a 120 EUR/t CO_2 tax on agricultural goods, which results in a carbon leakage of 111%. Meaning that reducing emissions within the EU will increase total global emissions (Nordin et al. 2019, p. 8). They therefore find that there is potential in reducing this leakage through a carbon tariff, like BCA.

The potential effect which CBAM has on the fertilizer markets can vary according to market characteristics. A study by Zhang et al. (2023) investigates the short-term effect disruption in Russian and Ukrainian food and fertilizer supply. It concludes that countries which have lower purchasing power per capita, a larger number of imported food commodities as well as a large population are more likely to experience a higher vulnerability to shocks from fertilizer supply (Zhang et al., 2023, p.5). This is an interesting result because when introducing CBAM to the EU market, the supply for imported goods to the EU be disrupted by an additional cost parameter. Because of the EU's strong purchasing power, as described in the paper, it can signal that the trade flow to the EU may not be that much changed in the short term, despite increased prices.

Overall, theory shows that distribution of free allowances works as a subsidy for production under EU ETS and can therefore limit the effectiveness of the EU ETS climate policy. Decreasing free allowances could cause an uneven cost increase among producers, and lead to reduced market competitiveness. In contrast CBAM can reduce the risk of carbon leakage, and potentially levelize the competitiveness between producers. A carbon tariff will raise the price on imports in the European market, making carbon-intensive goods, like fertilizers, relatively more expensive. Increased costs, higher prices, and potentially an uneven playing field affect industries and firms' profits differently, making it difficult to determine which will have a significant impact. However, such a shift could lead to more climate friendly production in the long term.

4. Model and data

In this chapter, we will present the methodology used for analyzing the future nitrogen fertilizer market. The simulated scenarios consist of market predictions for 2030, including free allowances in the EU ETS, CBAM and RED III. The structure of the model is inspired by Ringøen & Iversen (2021) master's dissertation from NMBU (Ringøen & Iversen, 2021, p.36-50). The model design, and its constraints, shape the boundaries of the analysis interpretations.

4.1 Choice of model

By constructing a multi-regional partial equilibrium model consisting of supply and demand dynamics, we have created an ex ante simulation of the impact a carbon tariff can have on the global fertilizer industry, as well as its effect on global emissions. The partial equilibrium model was chosen because it uses a small number of inputs to conduct a quick overview of the market dynamics. It is insightful despite its simplicity (Francois & Reinert, 1997, p.122). The model is programmed in Python using the SciPy optimize library.

The model consists of two markets: the EU market and the Rest of the World (ROW) market. In the EU market, only the EU countries and Norway are included. The ROW includes all consumers outside of the EU market. There are four producers, two of which produce in the EU market and are subject to the EU ETS (Norway and the EU), while the other two operate outside Europe without climate regulations (China and the ROW). Together, these producers account for the entire global production of nitrogen fertilizers. Transport costs and other trade barriers are not included in the model, allowing producers to easily shift sales between markets without incurring additional expenses.

ROW producers can sell to both markets, while the model constrain the EU producers to only sell in the EU-market. This is because the EU is characterized as a net importer of nitrogen fertilizer, meaning they import more than they export (Mambro, 2024). Despite Norway being characterized as a net exporter, the model is simplified to only let them sell to the EU market. This limitation can easily become a reality for Norway as they are more competitive as importers to the EU than other competitors from different countries, due to low carbon intensity. China is separated from the ROW, because they have a large market share of nitrogen fertilizers. Additionally, the high carbon intensity in coal-based production leads to exceptionally high emissions (FAO, 2024). This gives reason to assume that China differs from the ROW, and should be separated in the analysis. Because of high potential CBAM costs, as well as need to simplify the model, China only produces to the ROW market.

Furthermore, as explained in 3.1 the model assumes perfect competition. It is also assumed that the market is always in equilibrium and that producers are driven by profit maximization. Each producer is a price taker and cannot influence the nitrogen fertilizer market price. To maximize profits, it is therefore essential for producers to minimize their production and emission costs. In the model, we assume that there exist two prices on nitrogen fertilizer, one for each market. This is a reasonable market price simplification as pure solutions of nitrogen fertilizer products, such as urea and ammonium nitrate are relatively homogeneous goods (San Corporation, 2024). The model has no other trade restriction than the tariff, CBAM, which is directly linked to import of nitrogen fertilizer. Therefore, the price difference between the two markets equals the price of CBAM.

Regarding carbon leakage, the model solely accounts for leakage via the competitiveness channel, thereby omitting the potential indirect leakage impact of a carbon tariff through the international fossil fuel channel. The effects from the fossil fuel channel are unknown because the coal and gas prices are set exogeneous. In addition, the model only looks at one sector, while the fossil fuel channel influences prices across sectors, as described in chapter 3.4. Another limitation is that the model does not contain all the GHG emissions generated from fertilizers, excluding additional emissions from usage. Despite consumption of nitrogen fertilizer being a significant source for GHG emissions as described in subchapter 2.2.2, the EU's CBAM does not account for released emissions from using fertilizers at the farm.

4.2 Model scenarios for 2030

This section outlines the components of the four model scenarios conducted in the analysis. These scenarios are formulated based on three key components; the introduction of CBAM, the degree of free allowances in the EU ETS, and the inclusion of green hydrogen in RED III.

4.2.1 Scenario 1

To enable the model to effectively assess the diverse scenarios generated, we initially establish a reference scenario, scenario 1. Here we aim to simulate the nitrogen fertilizer market's state in 2030 if no adjustments are made from the present conditions. Essentially, we explore how the market would unfold if the amount of free allowances in the EU ETS remain unaltered, while base data change according to projections for 2030. This scenario serves as a foundation for analyzing the impacts of policy modifications, and can provide a perspective to understand the results observed in the other scenarios.

4.2.2 Scenario 2 & 3

The second and third scenarios take into account the gradual changes in specific climate policies. In other words, how allocation of free allowances in the EU ETS are reduced and how CBAM is integrated into the market. In the model, the implementation of CBAM is linked to the reduction of free allowances. Commitments by the European Parliament and the Council of energy intensity suggest a 51,5% decrease in free allocation by 2030. Initially, during the transitional phase, the CBAM factor should be set to 0%, since free allowances are

100% (scenario 1). However, by 2025, this percentage will start to increase annually. By 2030 CBAM is expected to be set at 48,5% of the production (Directive 2023/959, §46). Based on these EU regulations, the model encompasses two scenarios separating these policy changes. Scenario 2 demonstrates the gradual phasing out of free allowances to the 2030 level, while scenario 3 combines the phasing out of free allocations with CBAM implementation.

4.2.3 Scenario 4

The last scenario considers the type of hydrogen in the production of nitrogen fertilizer with the introduction of CBAM. As clarified in part 2.2.3, RED III requires that EU industries use 42% of hydrogen from renewable energy by 2030. Leaving only 58% of hydrogen from natural gas, which releases GHG emissions. In order to reach climate neutrality, the European fertilizer industry must undertake large investments in new technology when transitioning from gray to green hydrogen. Therefore, scenario 4 investigates the effect of these costs. In scenario 4 the phase-out of free allowances and CBAM is combined with green hydrogen according to the RED III requirements. Table 1 presents an overview of the different components applied to the producers in each scenario:

Scenario	**RED III (type of hydrogen)**	**Free allowances (% of benchmark)**	**CBAM (% of production)**
1	100% gray	100%	0%
2	100% gray	51,5%	0%
3	100% gray	51,5%	48,5%
4	42% green + 58% gray	51,5%	48,5%

Table 1: Outline of the different measures included in each scenario for 2030.

4.3 Demand functions

In the model, two demand functions are utilized, representing the total demand for nitrogen fertilizer in both the EU market and the global market. The demand functions are based on the market price. We assume a constant price elasticity, and therefore use isoelastic demand curves in the model. This implies that the percentage change in demand resulting from a percentage change in price remains consistent, regardless of the initial price and production level. Additionally, identical price elasticity is assumed across both markets. The demand functions are as follows:

$$D^{EU} = d^{EU}(p^{EU})^{e}$$
$$D^{ROW} = d^{ROW}(p^{ROW})^{e}$$

Where D^{EU} and D^{ROW} represent total demand for nitrogen fertilizer in the EU and the global market. p^{EU} and p^{ROW} are market prices, and e is the price elasticity. d^{EU} and d^{ROW} are parameters, which are calculated based on the price elasticity, the price and consumption of nitrogen fertilizer, further explained in subchapter 4.6.2.

4.4 Supply functions

In the model, we presume that the producer's supply function aligns with their marginal cost function. This assumption is based on the principle of perfect competition, characterized by the producer's willingness to sell until the cost of producing one unit exceeds the revenue from selling it in the market. As previously noted, producers strive to maximize profits, which entails minimizing costs to achieve this objective. Total costs have the following function:

$$TC_i\left(q_i^{EU}, q_i^{ROW}\right) = VC_i\left(q_i^{EU}, q_i^{ROW}\right) + FC_i$$

Where the producer's (i) total cost (TC_i) equals the variable costs (VC_i) of selling to both markets, EU and ROW, in addition to fixed costs (FC_i). q_i^{EU} and q_i^{ROW} represent the quantity the individual producer sells to the two markets. We assume that fixed costs are constant, because the model is set to short term predictions for 2030. This leaves only the variable cost as supply functions for the four producers in the nitrogen fertilizer market, giving the following functions:

China:

$$VC_C(q_c^{ROW}) = a_c \cdot q_c^{ROW^2} + cc \cdot q_c^{ROW}$$

Norway:

$$VC_N(q_N^{EU}) = a_N \cdot q_N^{EU^2} + gc_{EU} \cdot q_N^{EU} + ETS_N \cdot q_N^{EU}$$

European Union:

$$VC_{EU}(q_{EU}^{EU}) = a_{EU} \cdot q_{EU}^{EU^2} + gc_{EU} \cdot q_{EU}^{EU} + ETS_{EU} \cdot q_{EU}^{EU}$$

Rest of the world:

$$VC_{ROW}(q_{ROW}^{EU}, q_{ROW}^{ROW}) = a_{ROW} \cdot \left(q_{ROW}^{EU} + q_{ROW}^{ROW}\right)^2 + gc_{ROW} \cdot \left(q_{ROW}^{EU} + q_{ROW}^{ROW}\right) + CBAM \cdot q_{ROW}^{EU}$$

The production costs are divided into three cost components, two linear and one quadratic. The variable costs are assumed to have a quadratic component, resulting in marginal costs increasing linearly with production. The a_i parameter includes all other variable production costs than the producer's energy costs (*cc* & *gc*). The value of the a_i parameter will be further explained in section 4.6. In nitrogen fertilizer production, we have identified factors, calculated as cost components, that influence the cost levels for each producer. Tied together, this forms the basis for the producer's supply function.

4.4.1 Variable cost components

4.4.1.1 Producers energy costs

cc and *gc* are respectively coal and gas costs from production of nitrogen fertilizer, measured in euro per tonne nitrogen. Production of nitrogen fertilizer is an energy intensive process that uses hydrogen from natural gas or coal. As described in chapter 2.2.1, gas prices are therefore a large part of production expenses. Because China produces most of its nitrogen fertilizers from coal (Ju, 2019), the country is limited to only producing coal-based hydrogen in the model. The other producers use hydrogen from natural gas which differs in value based on the market. Each producer is assumed to be unable to influence coal and gas prices, so the energy costs are a linear cost component dependent on both energy intensity and gas/coal prices:

$$cc = eeff_c \cdot cp_c$$
$$gc_i = eeff_i \cdot gp_i$$

Energy intensity from production (*eeff)* is measured based on how much MWh is needed to produce per tonne of nitrogen, and prices cp_c and gp_i is measured in euro per MWh.

4.4.1.2 EU ETS: emissions costs

Producers within the EU ETS, Norway and EU must pay for their emissions by purchasing allowances. These allowances include both direct emissions and indirect emissions, according to ETS design. The indirect emission costs include emission from electricity production used in nitrogen fertilizer power plants. The purchased allowances are output based and can therefore be seen as variable costs calculated from the carbon intensity emitted in production. Furthermore, the EU regulation predicts a 51,5% decrease from benchmark in free allocation for 2030 (Directive 2023/959, §46). As explained in section 2.2.4 the number of free allowances granted depends on the carbon intensity of the producers' installations. The assumptions above give the following function for calculating the ETS costs:

$$ETS_i = \big((dir\,c.int_i + indir\,c.int_i) - (benchmark \cdot free.all)\big) \cdot qp$$

Where *dir c.int* and *indir c.int* are direct and indirect carbon intensity on average for each producer, measured in tonne CO_2 per tonne produced nitrogen. The benchmark refers to the expected product benchmark of nitrogen in 2030, measured in CO_2 per tonne nitrogen. *qp* is the quota price, measured in euro per tonne. The quota price calculated based on a price projection for 2030, further explained in 4.6.1. Only producers regulated by the EU ETS incorporate the ETS cost into their variable cost structures.

4.4.1.3 CBAM: Carbon tariff costs

In the model, it's the importer to the EU market who bears the cost of the carbon tariff, and the CBAM cost is included as a variable cost component in the importers supply functions. The emission costs for importers to the EU market are as follows:

$$CBAM = \left((dir\,c.int + indir\,c.int) \cdot (1 - free.all)\right) \cdot qp$$

The CBAM parameter is similar to the ETS_i cost component, but does not include benchmark and differs in how the phase-in of CBAM permits for 2030 is calculated. The percentage of in-phased CBAM permits for 2030 derives from the remaining percentage of free allowances in the EU ETS. The CBAM component also includes both direct and indirect carbon intensity (*dir c.int* & *indir c.int*) from production, measured in tonne CO_2 per tonne produced nitrogen. The CBAM cost component applies exclusively to the ROW supply function, which has the opportunity to import to the EU market.

4.4.2 Marginal costs

The optimal quantity is found by deriving the producers' variable costs with respect to the production quantity in each of the markets, q_i^{EU} and q_i^{ROW}, and then setting it equal to the price. As explained in chapter 3.1, in perfect competition the price equals marginal revenue, and the optimal quantity is where the price equals marginal cost. In other words, profit is maximized when this condition is met. The producer's marginal cost function is as follows:

$$MC_i^{EU,\,ROW} = \frac{\partial VC_i}{\partial q_i^{EU,\,ROW}}$$

This gives us the producers' profit-maximizing first-order conditions:

China:

$$MC_c(q_c^{ROW}) = p^{ROW} = 2a_c \cdot q_c^{ROW} + cc$$

Norway:

$$MC_N(q_N^{EU}) = p^{EU} = 2a_N \cdot q_N^{EU} + gc_{EU} + ETS_N$$

European Union:

$$MC_{EU}(q_{EU}^{EU}) = p^{EU} = 2a_{EU} \cdot q_{EU}^{EU} + gc_{EU} + ETS_{EU}$$

Rest of the World:

$$MC_{ROW}\left(q_{ROW}^{EU}\right) = p^{EU} = 2a_{ROW} \cdot q_{ROW}^{EU} + gc_{ROW} + CBAM$$

$$MC_{ROW}\left(q_{ROW}^{ROW}\right) = p^{ROW} = 2a_{ROW} \cdot q_{ROW}^{ROW} + gc_{ROW}$$

The left side show the producer's marginal revenue, and the right side shows the producer's marginal cost. Since the price is determined by the market, the marginal revenue equals the market prices in both markets. The right side of these equations represents the linear supply functions.

As explained previously China does not sell to the EU market and CBAM is therefore excluded as a cost component in the supply function. The Norwegian and the EU MC-equations does not include the CBAM cost components, but the producers are in return required to pay the ETS price. The two last equations represent how the ROW supplies nitrogen fertilizer to both the EU and the ROW market. When the ROW sells to the EU market the equation includes CBAM as a cost component, but it is not included in scenario 1

& 2 since these scenarios simulate a situation without CBAM. It is more profitable for a firm to sell to the EU market if the price difference between markets exceeds the cost of the carbon tariff. However, if the price difference is lower than the carbon tariffs, the focus shifts to selling outside of the EU market.

Additionally, scenario 4 in the model includes RED III as a climate policy in the fertilizer market. Such a scenario requires an expansion of the existing model. This is achieved by adding a variable for the producer's cost of green hydrogen (*cghi*) along with the production ratio for 2030 consisting of 42% green hydrogen, and 58% gray hydrogen. The RED III costs only affect the equations for the producer in the EU and Norway, because they are likely the only producers covered by the initiative. The scenario separates the constant parameter (a_i) for both types of hydrogen production in fertilizer plants. This is a simplification because it is likely that the two production pathways will have different values of a_i. The marginal cost curves with the inclusion of green hydrogen technology are in the model presented as follows:

Norway:

$$MC_N(q_N^{EU}) = p^{EU} = 2a_N \cdot q_N^{EU} + \left((gp_{EU} + ETS_N) \cdot 0{,}58\right) + (cgh_N \cdot 0{,}42)$$

European Union:

$$MC_{EU}(q_{EU}^{EU}) = p^{EU} = 2a_{EU} \cdot q_{EU}^{EU} + \left((gp_{EU} + ETS_{EU}) \cdot 0{,}58\right) + (cgh_{EU} \cdot 0{,}42)$$

4.5 Market equilibrium

In order to find the model’s market equilibrium, certain conditions must be met. Total demand (D) must correspond to production quantity and total supply (TS) in each market.

$$TS^{EU} = \sum_{i=4}^{4} q_i = q_{EU}^{EU} + q_N^{EU} + q_C^{EU} + q_{ROW}^{EU}$$

$$TS^{ROW} = \sum_{i=1}^{2} q_i = q_C^{ROW} + q_{ROW}^{ROW}$$

$$TS^{EU} = D^{EU}$$
$$TS^{ROW} = D^{ROW}$$

When these conditions are met, there exists an equilibrium representing the market solution. This is presented by a system of equations consisting of the demand functions (I and II) and the supply functions (III - VII) as described previously in this chapter (4.3 & 4.4.2). Leaving the following equation set:

$I.\ D^{EU} = d^{EU(p^{EU})^e}$

$II.\ D^{ROW} = d^{ROW(p^{ROW})^e}$

$III.\ p^{ROW} - 2a_C \cdot q_C^{ROW} - cc = 0$

$IV.\ p^{EU} - 2a_N \cdot q_N^{EU} - gc_{EU} - ETS_N = 0$

$V.\ p^{EU} - 2a_{EU} \cdot q_{EU}^{EU} - gc_{EU} - ETS_{EU} = 0$

$VI.\ p^{EU} - 2a_{ROW} \cdot (q_{ROW}^{EU} + q_{ROW}^{ROW}) - gc_{ROW} - CBAM = 0$

$VII.\ p^{ROW} - 2a_{ROW} \cdot (q_{ROW}^{EU} + q_{ROW}^{ROW}) - gc_{ROW} = 0$

In addition, the extended equation for scenario 4 (VIII - IX), affecting production for both EU and Norway. The two equations replace VI and VII in scenario 4:

$VIII.\ p^{EU} - 2a_N \cdot q_N^{EU} - ((gc_{EU} + ETS_N) \cdot 0{,}58) - (cgh_N \cdot 0{,}42) = 0$

$IX.\ p^{EU} - 2a_{EU} \cdot q_{EU}^{EU} - ((gc_{EU} + ETS_{EU}) \cdot 0{,}58) - (cgh_{EU} \cdot 0{,}42) = 0$

The equation set above consists of seven equations and nine variables. The unknown variables are the following, p^{EU}, p^{ROW}, D^{EU}, D^{ROW}, q_C^{ROW}, q_N^{EU}, q_{EU}^{EU}, q_{ROW}^{EU}, q_{ROW}^{ROW}.

By solving the model optimization problem, as described above, we can find the market price for both markets, the producer's production volume, total demand and number of units sold to both markets. Producers will continue to sell to the market as long as the price is higher or equal to their marginal costs.

4.6 Data

This section will provide the base data upon which the simulations are constructed. The data is mainly based on projections towards 2030, which are imperfect and sometimes incomplete due to shortage of research. The data is therefore based on assumptions and simplifications which will be further clarified in this subchapter.

When collecting data for the nitrogen fertilizer industry it is important to distinguish data that is provided per tonne nitrogen, and per tonne nitrogen product, which could include various quantities of nitrogen. In the analysis all data which is not provided in the correct unit, is converted to tonne per nitrogen. Some of the data is also given in tonne per ammonia and tonne per nitric acid, which also has to be converted to the correct unit. In the model, the following default converting table from FAO has been used (FAO, 2023, p.4):

Nitrogen fertilizer	**Percentage of nitrogen**
Ammonia	82,0%
Urea	46,0%
AN (ammonium nitrate)	33,5%
CAN (calcium ammonium nitrate)	26,0%
NPK (mixed fertilizer)	15,0%

Table 2: A converting table for percentage nitrogen within various types of nitrogen fertilizer products.

The data in table 2 is also the same as the converting values used by Yara (Yara, 2022, p.96), indicating that the conversion numbers are used by the fertilizer industry as well as in research. For further data description, all data collected in US dollars is converted to euros by a 5-year average valuta ratio equivalent to 0,897 (European Central Bank, 2024). The exchange rate between Chinese yuan to euros (CNY) is also based on a five-year average, and set to 0,132 (Investing.com, 2024).

4.6.1 EU policy

When calculating the ETS costs for 2030, benchmark values as well as projections for the ETS price are applied. In the model the benchmark for 2030, is based on the already set EU starting benchmark for ammonia for 2021-2025 (Regulation 2021/447, Annex 2). It is reduced yearly by 1% towards 2030 due to the European Commission's ambitions for reduction (Redshaw, 2024). As the definite benchmark for 2030 is yet to be decided, the model benchmark was calculated to 1,749 tonne CO_2 eq / tonne nitrogen, based on the assumptions explained.

The EU ETS price is projected differently according to various studies. One study by Cail et al. (2023) projected the price to be 70 €/ t CO_2 eq (Cail et al., 2023, p.9), while another anticipated the price to increase to 147 €/ t CO_2 eq (Glushchenko, 2023). The ETS price in the model is therefore set to the average ETS price of these projections, equivalent to 108,5 € / t CO_2 eq.

4.6.2 Demand curves

The demand curves are conducted based on two different demand parameters, d^{EU} and d^{ROW}. These parameters are built on aggregated demand data for 2018, a year chosen based on available data, as well as the year being representative for a normal year, before the pandemic, the Ukrainian war and the energy crisis. The parameters are based on data for price, elasticity and consumption. The nitrogen price of 486 € / t N is extracted from the average global 2018 price for urea (Statista, 2023), and converted to the price for nitrogen based on table 2. The elasticity used is the same as for the model, while consumption is collected from the UNs fertilizer and agriculture organization (FAO, 2024). Demand is assumed unchanged from 2018 to 2030.

The price elasticity used in the demand curves for the two markets is based on a paper which estimates the elasticity to be -0,5 (Finger, 2012, p. 18). This is also supported by other research findings such as a Danish study that estimates the elasticity to be between -0,69 and -0,24 (Hansen, 2004, p. 14).

4.6.3 Supply EU and Norway

In line with the demand curves, the supply curves also include parameters based on historical data for 2018. In order to calculate these parameters (a_{EU} & a_N), the same fertilizer price as explained in section 4.6.2 is applied. Both production functions also use the same 2018 average EU natural gas price (Trading Economics, 2024a), and production quantity aggregated from FAO (FAO, 2024). Historic ETS costs for 2018 were difficult to find. They were therefore instead calculated based on carbon intensity in 2018 for Norway, and due to lack of 2018 data, 2020 for the EU. The ETS costs were also accumulated from the EU benchmark for 2018 (Regulation 2011/278, Annex 2), together with the average EU ETS price for the same year (European Environmental Agency, 2019). In 2018 the benchmark is 100% of the free allowances, which gives 0 ETS costs for Norway due to a lower carbon intensity than the benchmark.

The natural gas price in the supply functions, which stands for large parts of the total production costs for gray hydrogen, is gathered from a projection by the Oxford Institute. It projects prices to be between 8 $ and 5 $ / MMbtu for Europe in 2030 (Fulwood, 2023, p.2). In the model the price is set to the average of these prices, equivalent to 6,5 $, and converted to euros based on the valuta ratio mentioned earlier in the data chapter. Since natural gas prices are regional, the model uses the same price for both EU and Norwegian producers.

In the model energy intensity, which is the usage of fuel per tonne of nitrogen, for both the EU and Norway are gathered from historic EU data (Balafoutis et al., 2022, p.9). The same intensity is used for Norway due to lack of country specific data. Natural gas costs per tonne of nitrogen is found by multiplying natural gas price with energy intensity, as shown in the equation of section 4.4.1.1. For scenario 4, costs for green hydrogen are collected from a report by DECHEMA on EU and Norwegian green hydrogen perspectives for 2030. In this report costs for green hydrogen in Norway are found to have slightly lower costs than the EU, due to lower green electricity costs. We assume that the EU produces all of its green ammonia in southern Europe because of cheaper production in this area (Ausfelder, 2022, p.9).

Carbon intensity used for calculating the ETS costs, are collected separately for Norway and the EU. Direct GHG emissions from Norwegian producers (Yara) are gathered from the Norwegian Environment Agency in 2021 (Norske Utslipp, 2024). The total emissions are then divided by total production of nitrogen fertilizers produced the same year (FAO, 2024). For the indirect emissions, electricity usage for ammonia production (Ashraf, 2022) is multiplied by prediction for carbon intensity in the European electricity grid in 2030 (Enerdata, 2024). EU carbon intensity for both indirect and direct emissions is found in an outlook report for 2030 (Ausfelder, 2022, p.28). Norwegian carbon intensity is based on historical data, not projections, due to lack of country specific data.

4.6.4 Supply ROW and China

The cost parameter (a_{ROW} & a_C) for the supply in ROW and China is similarly to the European supply curves based on historic data. The parameters are also extracted from 2018 data, and use the same global price for fertilizers. The main difference from the EU and Norwegian parameters is that the ROW and Chinese producers do not pay for emissions, as CBAM is yet to be introduced in 2018. Production data for the ROW is calculated from FAO (2024) by subtracting world production with EU, Chinese and Norwegian production. Chinese production data is collected from the same resource.

In order to calculate the cost parameters, fuel prices for the two producers have been collected. The ROW fuel cost for 2018 is based on the historic natural gas price for the largest world producers. From 2002 to 2021 USA and India are on average the second and third largest producers of nitrogen fertilizers after China (FAO, 2024). For simplicity reasons, the natural gas price was set to the average natural gas price in 2018 for these two countries. The natural gas price for the US is gathered from the average US Henry Hub price for 2018 (Energy Institute, 2023, p.34) while the Asian price is set to the average spot price in the Asian market the same year (IEA, 2020). For China the price is set to the average coal future price traded on the international market for 2018 (Trading Economics, 2024b). The same energy intensity values as used in fuel cost parameter, is used in calculating the cost parameter.

The ROW fuel cost parameter for 2030 is based on the predicted natural gas price for USA and India, as these countries will likely remain large producers also in 2030. The natural gas price in the model is set to the average forecasted natural gas price for these two countries, equivalent to 5,975 $ / MMBtu (Deloitte, 2022, p. 12). The aggregated energy price for Chinese production is 400 CNY per tonne of coal, and is collected from a forecast for Chinese coal price in 2030 (Ding et al., 2018, p.194).

With limited predictions for energy intensity in fertilizer production towards 2030, energy intensity is conducted from historic data. ROW energy intensity is based on an approximate value for US nitrogen fertilizer for 2019 (Farm Energy, 2019), and for China the data is collected from 2016 research (Wendołowski, 2019, p.10). These values are respectively 25000 BTU / tonne nitrogen for the ROW and 44,255 GJ / t ammonia for China. Due to old data, it is likely that Chinese energy intensity will improve towards 2030, relative to the input data.

Direct carbon intensity for the ROW and China is collected from 2018 data by dividing GHG emissions from manufacturing by production. For the ROW the carbon intensity is calculated to 3,27 t CO_2 eq / t N based on average global emission intensity, excluding China and the EU emissions. Chinese carbon intensity is calculated to 5,74 t CO_2 eq / t N (Ledo et al. 2022, p.3). Indirect energy usage through electricity is set at 0,3 GJ / t ammonia for the ROW, and 3,7 GJ /t ammonia for coal-based production in China (Ashraf, 2022). To calculate indirect emissions electricity usage is multiplied by regional electricity price outlooks for 2030 (Enerdata, 2024).

5. Analysis and Results

This part of the paper will present the results from the simulations of the model's four scenarios. Firstly, results on prices, production quantity, demand, revenue and emission level are analyzed. Next, the section will provide a scenario assessment, followed by a sensitivity analysis on particular uncertain variables within the model. Only the most important results are filtered out, explained and visualized, but all results can be found in the annex at the end of the paper.

5.1 Scenario 1

Scenario 1 can be seen as a reference scenario that represents expected data for 2030, where the ETS policy is unchanged from current policy. This is a scenario where EU and Norwegian fertilizer firms are granted 100% of allowances for free if they produce fertilizers under a set benchmark for emissions per output. In this scenario the EU fails to carry out plans to phase out free allowances and do also fall out on their ambition to implement CBAM and RED III. In scenario 1 foreign industry experiences no carbon tariff on imports to the EU.

5.1.1 Market situation

In scenario 1, the price is the same in the EU market and the ROW and is listed at 465 € / tonne nitrogen. The EU market is 10% the size of the world market which is equivalent to 12,4 million tonne nitrogen.

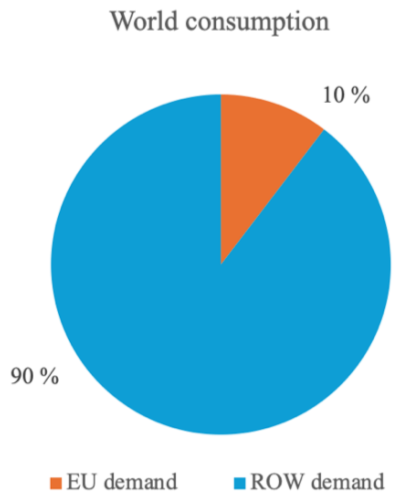

Figure 6: Share of world consumption for the EU and ROW market.

In scenario 1 the ROW has the largest market share for both the ROW and the EU market. EU and Norwegian producers stand for 43% of the EU demand, and the market imports the rest from the ROW producers. In the ROW market the ROW producers produce 66% of demand, while China produces 34%.

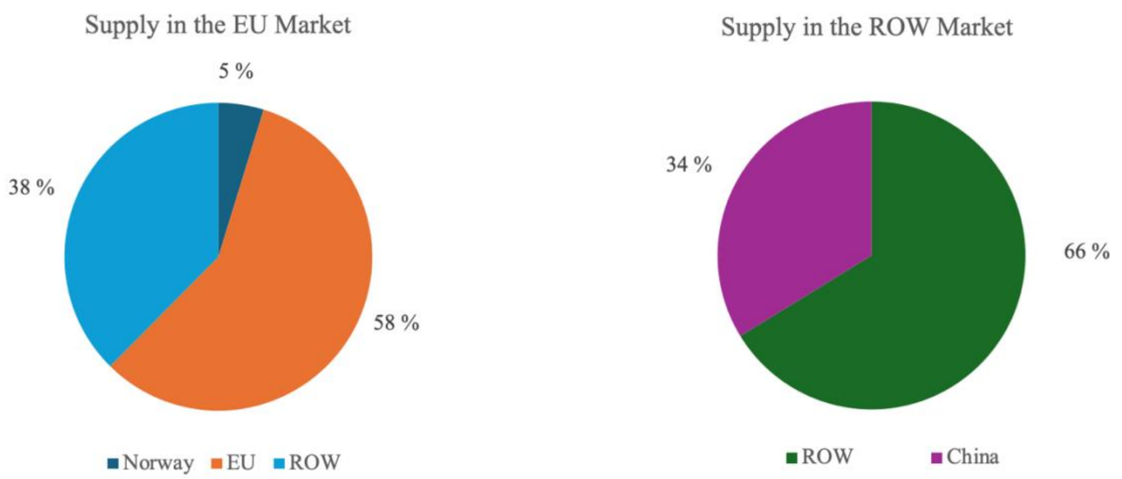

Figure 7: Share of production by countries to the EU and ROW market.

5.1.2 Revenue and costs

Based on the world price for nitrogen fertilizer, and the production quantity by the various countries, gross revenue is calculated. Gross revenue is used instead of net revenue, due to limited information on total costs. In scenario 1 the EU producers earn 3,3 billion € in gross revenue, while Norway earns 274 million €.

In scenario 1 ETS costs are 0 € / t nitrogen for Norway, and 68 € / t N for the EU. The ETS costs are 0 for Norway because the carbon intensity for Norwegian producers is lower than the set EU benchmark. Since the carbon intensity for Norway is 1,305 t CO_2 eq / t N, and the benchmark is 1,749 Norway grants 100% of allowances for free. For the EU the carbon intensity is at 2,378 t CO_2 eq / t N which means they are over the benchmark, and are required to pay emission costs equivalent to 15% of their revenue (table 4). The percentage rate is zero for Norway due zero ETS costs.

Scenario 1: Gross revenue	
Producers	Revenue in M €
EU	3326
Norway	274
China	16802
ROW	35135

Table 3:Gross revenue realized by producers in scenario 1.

Scenario 1: ETS costs		
	ETS costs in M €	ETS costs/ revenue
EU	488	15 %
Norway	0	0 %

Table 4: ETS costs for EU and Norwegian producers in scenario 1.

5.1.3 Emissions

In scenario 1 ROW emits the most emission from production because they are the largest producers in the world. China, despite only producing about 30% of the world's nitrogen fertilizer demand, stands for large emission shares. This is due to Chinese emission intensive production which in the model is set to 6,29 t CO2 eq / t N.

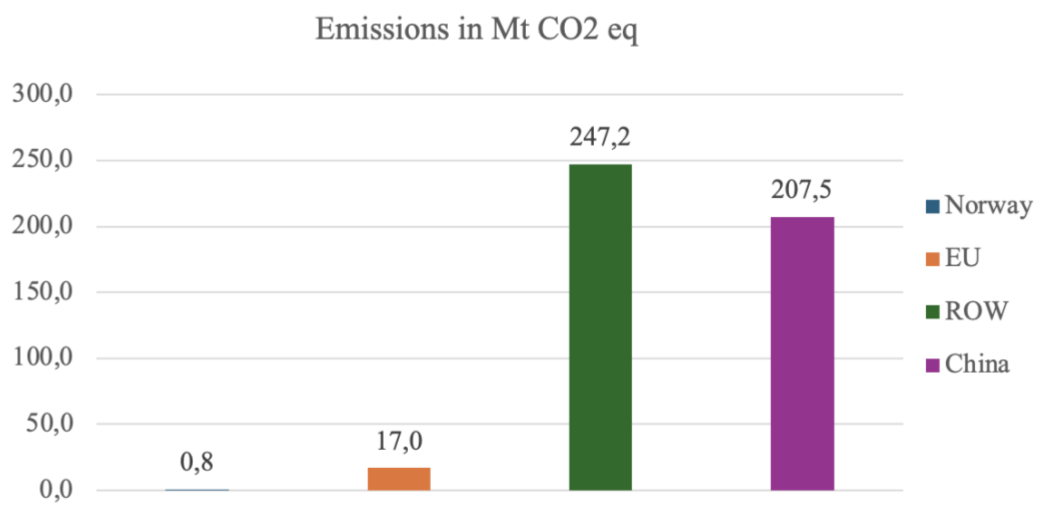

Figure 8: Total direct and indirect greenhouse gas emissions from nitrogen fertilizer production by country in scenario 1.

5.2 Scenario 2

Scenario 2 represents a situation where the EU follows through on their ambitions for ETS phase out of free allowances according to current plans, without limiting foreign imports to the region. This scenario is created to simulate a situation where the EU only considers domestic emission reduction, and does not consider the global effect, industry competitiveness or carbon leakage. There is therefore no CBAM introduced in this scenario, but the EU ETS free allocation has been reduced to 51,5%, according to EU ambitions as explained in section 4.2. All other conditions are unchanged from scenario 1.

5.2.1 Market situation

Due to increased costs for EU producers the global nitrogen fertilizer price increases by 2% in scenario 2 compared to scenario 1, and is set at 474 € / t N. The price is the same in the EU market and the ROW market because of zero trade restrictions. As a result of increased prices global demand reduces, which causes reduction in global production. In scenario 2 the largest changes in production from scenario 1 occur for the EU market producers, which is EU, Norway and the ROW. The European industry faces increased costs due to ETS costs increasing to 45 € / t N for Norway, and 160 € / t N for the EU. As a result, the ROW, which is not subject to pay the CBAM tariff in scenario 2, replaces large parts of the domestic industry in the EU through imports to the EU market. The total production in the ROW increases by 4 million tonnes, while China increases by 1 million tonnes. The EU and Norwegian production are reduced by respectively 88% and 22%. The reduction of supply is larger for the EU due to production being more carbon intensive than Norwegian production, which means that the EU must pay a larger share of ETS costs.

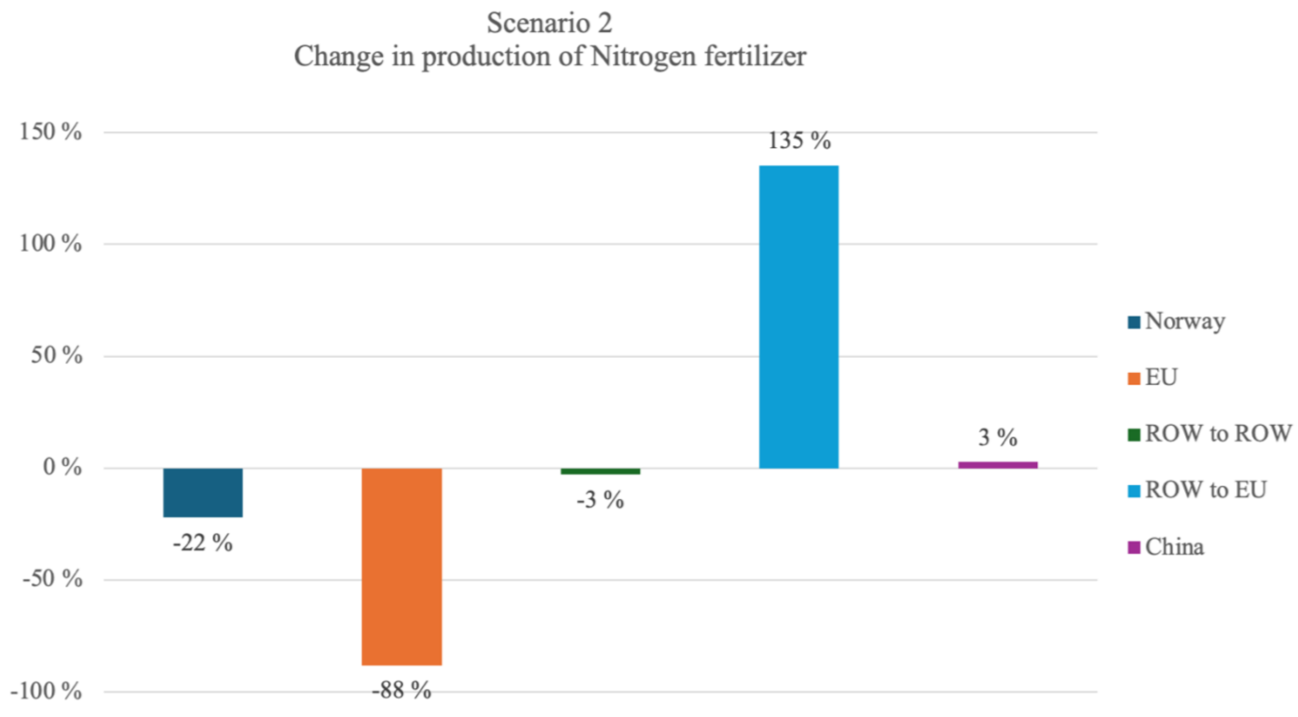

Figure 9: Percentage change in production in scenario 2 compared to scenario 1.

5.2.2 Revenue and costs

Compared to scenario 1, the EU and Norwegian industry loses 2,4 billion € in gross revenue when the free allowances decrease to 51,5%. This is equivalent to an 88% decrease in EU revenue, and a 20% decrease in Norwegian revenue. In scenario 2 both producers in the ROW and China benefit from the ETS adjustments without the CBAM. Revenues in the ROW are directly affected due to increased imports to the EU, while Chinese producers benefit indirectly, as they increase production in the ROW.

Scenario 2: Gross revenue		
	Total revenue in M €	Percentage change in revenue
EU	403	−88%
Norway	218	−20%
China	17600	5%
ROW	37885	8%

Table 5: Revenue in scenario 1 and percentage change in revenue from scenario 1 to 2.

Due to a large fall in EU production, the total ETS costs in the EU also decreases. The share of ETS costs/revenue increase for both EU and Norway which shows that the ETS costs have greater importance on gross revenue than in scenario 1. The reason is due to the substantial loss of free allowances in scenario 2.

Scenario 2: ETS costs		
	Total ETS costs in M €	ETS costs/ revenue
EU	136	34%
Norway	21	10%

Table 6: ETS costs paid by EU and Norwegian producers.

5.2.3 Emissions

As a result of the decreased production in the EU and Norway, the European region experiences large emission reduction in scenario 2. ROW and China increase emissions because of increased supply. Despite an 88% decrease in GHG emissions from the European producers, the total global nitrogen fertilizer industry experiences a slight increase of 4 million tonnes CO_2 eq. The global emissions increase despite a decline in global production. This is because producers with higher carbon intensity get a larger world market share. The carbon leakage from scenario 1 to scenario 2 is in the model calculated to 128%. The leakage rate represents the carbon leakage from changing the ETS free allowances from 100% to 51,5%. The calculated percentage rate does not show the percentage change in carbon leakage from scenario 1 to scenario 2, nor a total leakage rate for implementing the whole ETS system. This is because the reference scenario (scenario 1), is a scenario with already implemented climate policy where the leakage ratio is unknown.

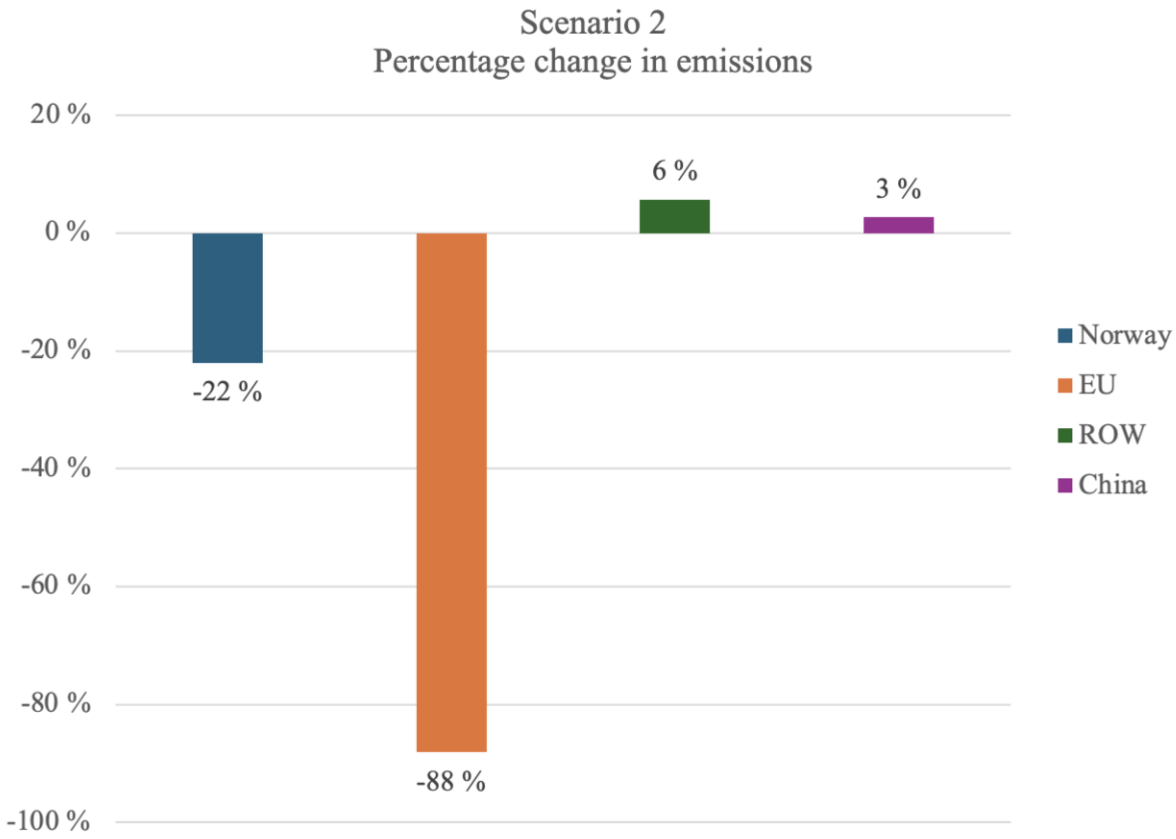

Figure 10: Percentage change in emissions from scenario 1 to scenario 2.

5.3 Scenario 3

Scenario 3 is the first scenario which introduces a carbon tariff on imported nitrogen fertilizers to the EU. In the model the CBAM tariff is based on the ETS price and free allocations in the EU, shown in the equation of section 4.4.1.3. The CBAM cost in the model is however larger than the EU ETS cost because of a more carbon intensive industry in China and the ROW. Since RED III is not enforced, the scenario therefore only looks at the effect of reducing free allowances while implementing CBAM. All other conditions are equivalent to the conditions in scenario 2.

5.3.1 Market situation

Scenario 3 features two distinct prices for the EU market and the ROW. The EU market experiences a 28% price increase which reduces demand in the region by 12% compared to scenario 1. The ROW encounters a price reduction of 2% in comparison to scenario 1. The price is lower in the ROW, because there is a larger supply to the ROW due to increased CBAM costs. Including CBAM in the model reduces all incentives for imports from the ROW to the EU. Due to stricter carbon policy regulations and higher carbon intensity in the ROW, importers from ROW to the EU face a tariff that's twice the ETS price paid by EU producers (table 8). The ROW importers to the EU are therefore zero in scenario 3.

Because of the lower carbon intensive production, the EU and Norwegian industry is more competitive in the EU market. The producers experience an increase of produced nitrogen fertilizers by respectively 41% and 52%. Chinese production is slightly reduced by 2% because the ROW is now utilizing more fertilizers domestically, instead of exporting to the EU.

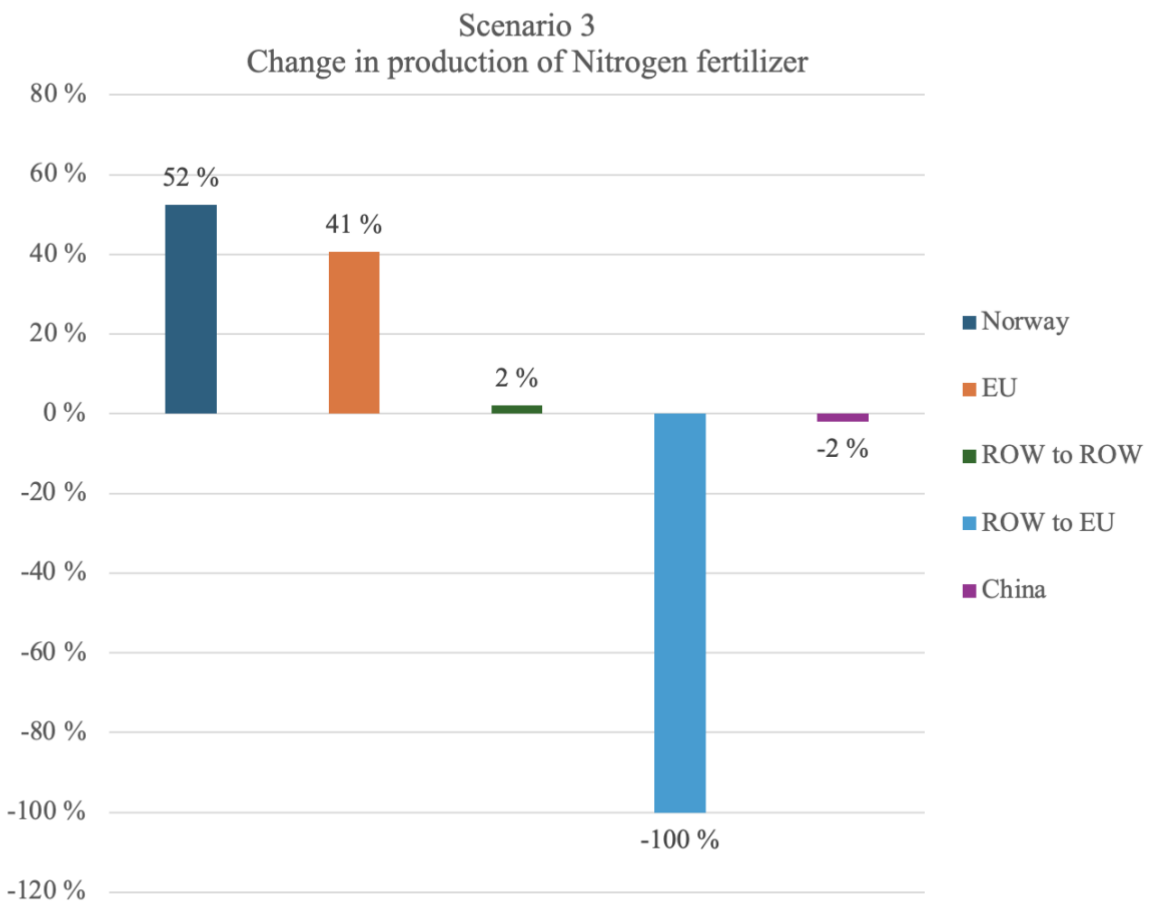

Figure 11: Percentage change in production of nitrogen fertilizers by country from scenario 1.

5.3.2 Revenue and costs

The rise in production for the European producers is mirrored in their boost in gross revenue. Including CBAM increases the gross revenue for the EU to 6 billion €, and 536 million € for Norway compared to Scenario 1. This is due to the larger EU market share, but also due to price increase. The implementation of CBAM results in reduced revenue for both China and the ROW. ROW producers face increased costs on imports to the EU, while Chinese producers suffer from a loss of market share to the ROW. Additionally, both producers undergo a slight price decrease, further diminishing gross revenue.

Scenario 3: Gross revenue		
	Total Revenue in M €	Percentage change in revenue
EU	5991	80%
Norway	536	95%
China	16227	−3%
ROW	33164	−6%

Table 7: Total revenue and change in revenue from scenario 1 to scenario 3.

The total costs for ETS increases as compared to scenario 1, and 2 for Europe and Norway. The reason for increased costs between scenario 2 and 3 comes from the expanded fertilizer production for both producers. The costs are represented in the increased fertilizer price in the EU, and indirectly paid by consumers. The producers increase gross revenue because the demand is inelastic, as a 28% price increase only reduces demand by 12%. Although the total ETS costs increase in scenario 3, the ETS costs/ revenue is slightly lower than in scenario 2 because of a higher price for nitrogen fertilizer.

In scenario 3, the CBAM cost for ROW producers amounts to 216 € / t N, while Chinese producers would contend with a CBAM tariff of 331 € / t N if importing to the EU region. These costs are much greater than the internal EU cost of 93 € / t N, which is why foreign ROW imports to the EU are nonexistent in scenario 3.

Scenario 3: ETS-/ CBAM costs			
	ETS-/ CBAM cost in €/ t N	Total ETS/ CBAM costs	ETS costs/ revenue
EU	93	1614	27%
Norway	26	41	8%
China	331	0	-
ROW	216	0	-

Table 8: ETS & CBAM costs for producers in scenario 3.

5. 3.3 Emissions

The EU and Norway increase GHG emissions in scenario 3 due to larger production quantities. Conversely, the ROW and China experience decreased emissions due to reduced production levels. As a result, the total global industry sees a decrease in emissions by 1,5% compared to scenario 1. Given the carbon leakage formula described in section 3.4, calculating carbon leakage is illogical when emissions increase in the region where the policy is implemented. Calculating the carbon leakage rate is therefore irrelevant in scenario 3. Since global emissions decline as a result of the CBAM, it nonetheless indicates that CBAM is a more effective climate policy than free allowances in scenario 1.

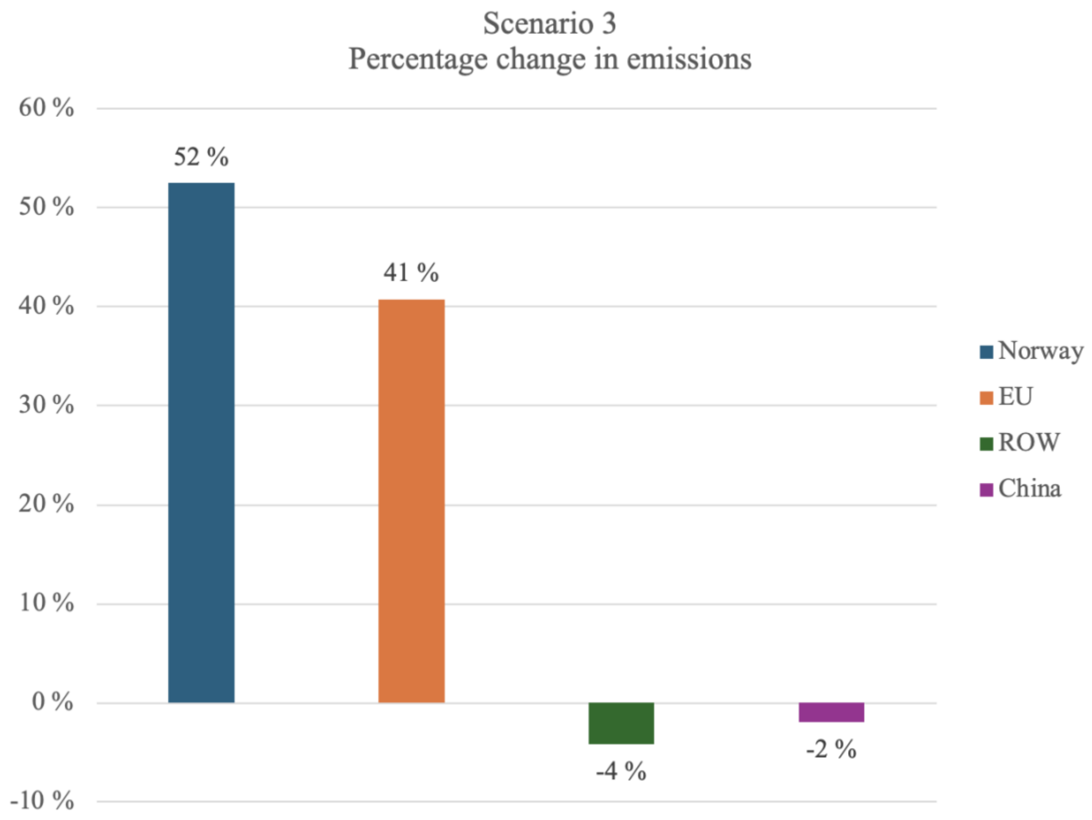

Figure 12: Percentage change in emissions from scenario 1 to scenario 3.

5.4 Scenario 4

Scenario 4 combines the policies in scenario 3, which are the reduction of free allowances and inclusion of CBAM, with the implementation of green hydrogen requirements in RED III. In the model EU and Norwegian producers are required to produce 42% of hydrogen from renewable energy. Since the costs for green hydrogen are expected to be higher than those for gray hydrogen, the model restricts the production of green hydrogen for EU and Norwegian producers to exactly 42%, with no flexibility for greater or lesser production. The rest of European production is produced from gray hydrogen. ETS price, CBAM, free allocation, and other conditions are unchanged from scenario 3.

5.4.1 Market situation

When RED III is introduced, the EU loses all market share, while Norwegian production is significantly declined. The prices in the EU market increase by 39%, while the prices in the ROW only increase by 2%. The increase in EU prices causes demand in the EU to drop by 15%. Due to rising costs for EU producers, the ROW increases imports to the EU.

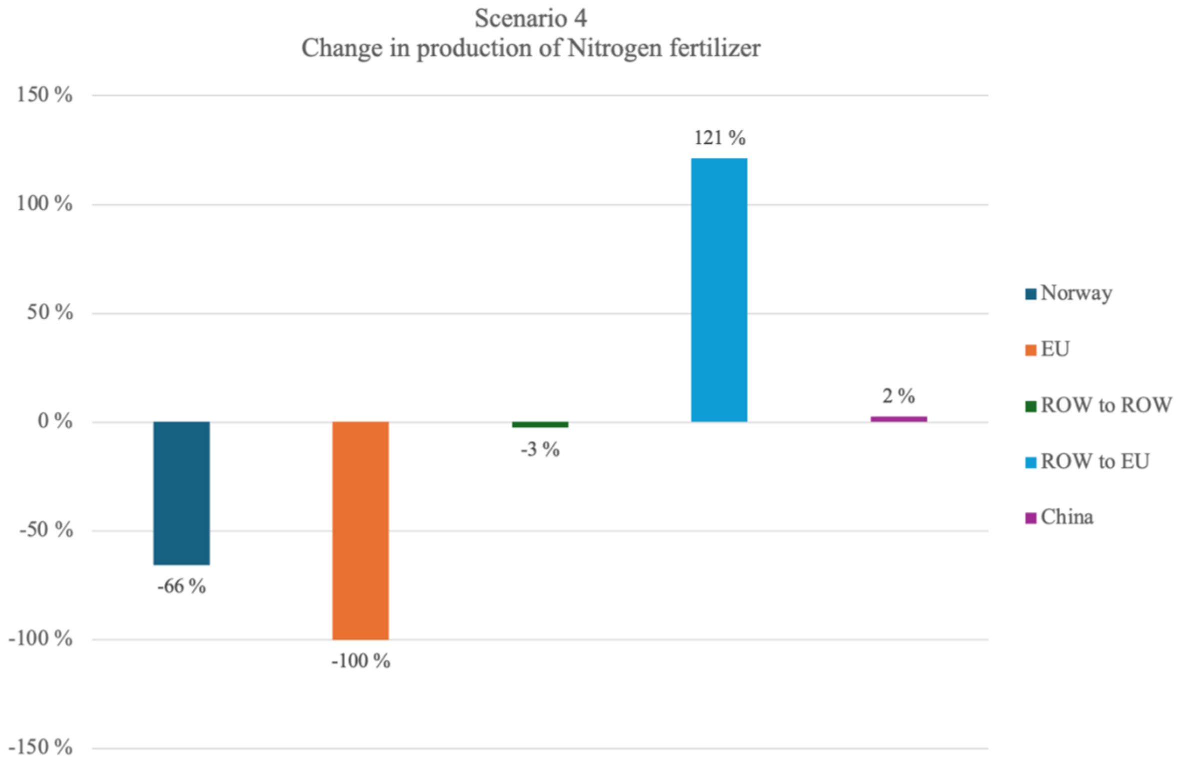

Figure 13: Change in production by country from scenario 1 to scenario 4.

5.4.2 Revenue and costs

With no EU production in scenario 4, EU gross revenue declines by 100%. Norwegian gross revenue experiences a 52% decrease, while the ROW sees a 12% increase in revenue.

Scenario 4: Gross revenue		
	Total revenue M €	Percentage change in revenue
EU	0	−100%
Norway	131	−52%
China	17516	4%
ROW	39384	12%

Table 9: Percentage change in gross revenue from scenario 1 to scenario 3.

The EU ETS cost per tonne of nitrogen is decreased compared to scenario 2 and 3. This is because EU and Norwegian producers do not pay ETS costs for the production of green hydrogen. They therefore only need to pay ETS costs for 58% of the production. Despite reduction of ETS costs / tonne of nitrogen, the cost of green hydrogen in the EU is too large to justify any EU production. In Norway the prediction for green hydrogen costs is slightly lower than in the EU because of cheaper electricity production (Ausfelder, 2022, p.9). Due to lower ETS and green hydrogen costs, Norway still supplies a small amount to the EU market. The total cost of green policy (RED + ETS) for Norway increases to 64% of gross revenue, which is a significant cost for the producer.

In scenario 4 the ROW still faces the same CBAM costs per tonne of nitrogen as compared to scenario 3. Although the ROW is required to pay a CBAM cost of 216 € / t N when importing to the EU, these costs are much lower than the costs EU and Norway meet under RED III. The ROW is therefore incentivized to import to the EU despite the significant costs. In scenario 4 the ROW increases CBAM costs from 0 to 2227 M € as compared to scenario 3 due to a significant increase in imports from ROW to the EU. For ROW importers to the EU, the CBAM cost equates to 33% of their gross revenue. The CBAM cost is reflected in the increased EU price but has only a small effect on the price in the ROW market.

Scenario 4: Costs for RED & ETS/ CBAM					
	ETS-/ CBAM cost in € / t N	Total ETS/ CBAM costs M €	Green technology cost € / t N	Total cost of green technology M €	Total green policy cost/ gross revenue
EU	93	0	425	0	-
Norway	26	5	389	79	64%
China	331	0	0	0	0%
ROW to EU	216	2227	0	0	33%

Table 10: Green policy costs for scenario 4.

5.4.3 Emissions

GHG emissions from nitrogen fertilizers in the EU decrease by 100% due to zero production. Norwegian production experiences an emission decrease of 80%, while the ROW and China increase emissions. In total the overall GHG emissions do not change, and the carbon leakage rate is calculated to 99% from scenario 1. The carbon leakage rate includes the effect from decreasing the ETS free allowances, including CBAM and introducing RED. The leakage is caused by replacing EU and Norwegian production with more carbon intensive fertilizers from the ROW, and replacing some ROW fertilizer with even more carbon intensive fertilizers from China.

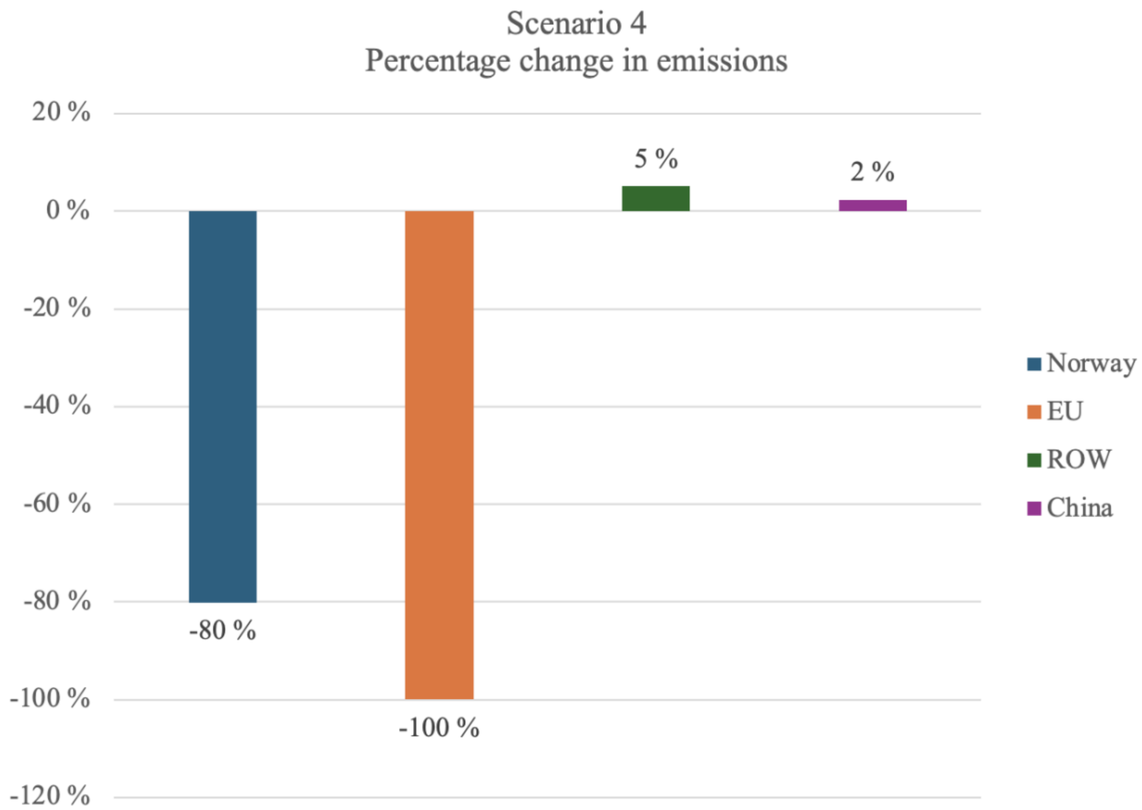

Figure 14: Percentage change in emission from scenario 1 to 4.

5.5 Scenario assessment

The assessment of the scenarios in the model relies on whose interests one wishes to prioritize. If considering the perspective of the EU and Norwegian industry, scenario 3 is favorable because it increases revenue while eliminating competition from the ROW. Scenario 3 is also attractive from a global environmental perspective because it is the scenario where GHG emissions reduce the most. Scenario 3 does however fail to reduce greenhouse gas emissions within the EU, and is therefore less desirable if the EU wishes to comply with EU's obligation to reduce domestic emissions.

From the perspective of China and the ROW, scenario 2 and 4 are the most attractive scenarios. In scenario 2, the ROW and China increase market share due to large ETS costs for European producers, while at the same time are exempted from paying an emission tariff.

Scenario 4 is also desirable for the ROW but provides a slightly smaller net revenue, due to large CBAM costs on imports to the EU.

In scenario 4 the EU domestic emission reduces while the global GHG emissions increase. In this scenario the domestic industry in the EU is also exterminated and the Norwegian industry highly reduced, making it very unattractive for domestic suppliers. On the other hand, the EU increases revenue from the CBAM tariff, but this revenue amounts to only 25% of the gross revenue earned by the EU and Norwegian industry in scenario 3. With current input data, scenario 4 is highly unattractive for EU and Norwegian industry, as well as for global GHG emissions. Whether or not uncertainty in the inputs used in the model could cause changes in the scenario results will be further analyzed in the next subchapter.

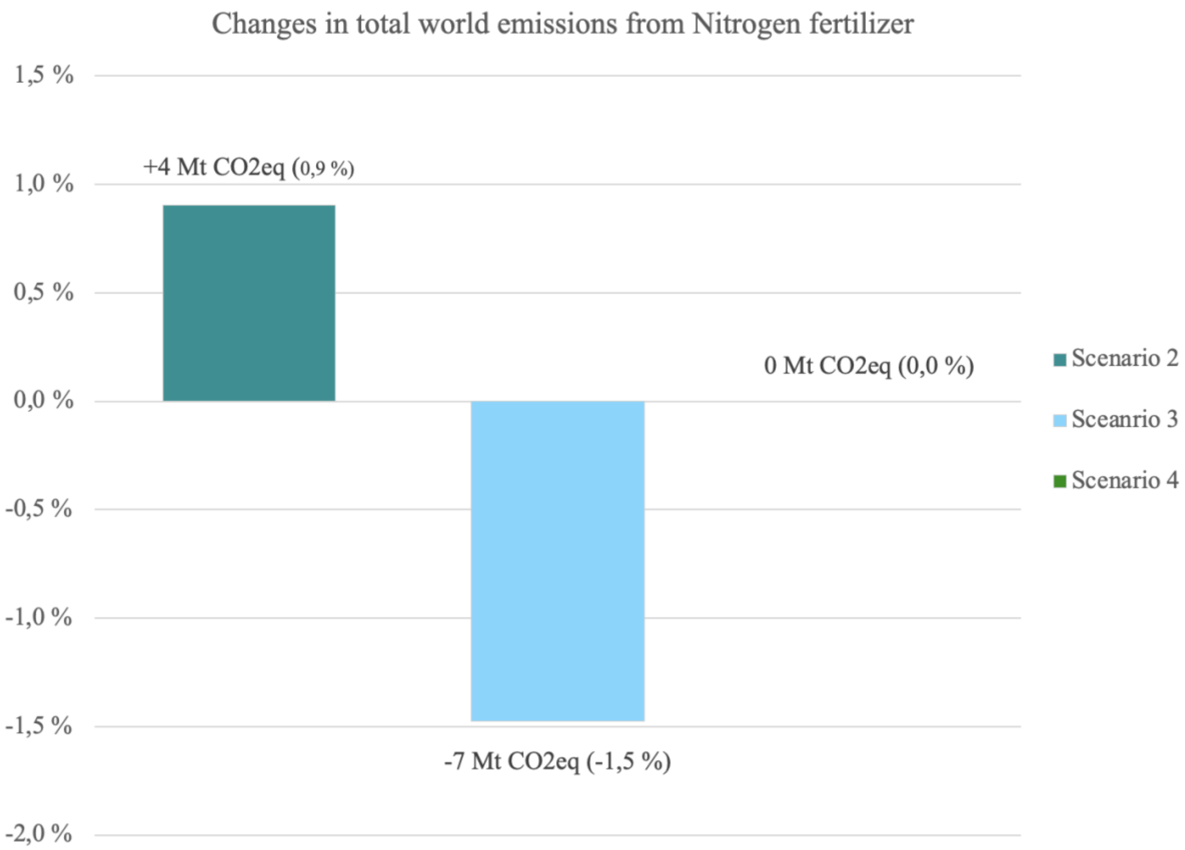

Figure 15: Changes in total global emissions from the nitrogen fertilizer industry for the various scenarios. Reference scenario is scenario 1 with an emission level of 473 Mt CO2 eq.

5.6 Sensitivity analysis

The simulation model in the analysis is built on assumptions, simplifications and uncertain input parameters for the future. In light of these uncertainties results should be viewed with a critical perspective. In order to look at how important some of these uncertainties are for the results of the model this section provides an analysis of sensitivity. Based on their potential importance for the results and projected volatility, gas price, the EU ETS price, demand elasticity and costs for green technology are the parameters picked out to be a part of the sensitivity analysis. In order to look at how changing the parameters affect results in the model, the parameters are changed individually while everything else in the model remains unchanged. “Reference values” in this sensitivity analysis refers to values aggregated in the main model which serves as a benchmark to compare the results from the sensitivities.

5.6.1 Higher or lower natural gas prices

Natural gas prices fluctuate over short and long periods, depending on demand, supply, weather and availability of alternative energy substitutes (DailyFX, 2024). Changes in supply and demand of fertilizers may have an impact on demand for natural gas and therefore influence prices. This effect may cause errors in the simulation as natural gas is simplified as an exogen parameter in the model. As earlier mentioned in chapter 4.6.3, the gas price in the model is based on an average between projected European “roof” and a “floor” gas price for 2030, respectively 8 $ and 5 $ / MMbtu (Fulwood, 2023, p. 2). In the sensitivity analysis, the "roof" and the "floor" are used individually as inputs to assess how variations in gas prices affect the model's outputs.

The natural gas markets can be divided into four main world regions, but could be trending towards a more global market in the long term as LNG products are becoming more affordable (GECF, 2024). In the sensitivity analysis we have therefore chosen to change the gas price in the ROW, according to the percentage change between the “roof”/ “floor” price and the average price in Europe. This way the results will represent equal changes in prices for the ROW and EU equivalent to +/-23%. The natural gas price for the ROW in the model is set to 5,98 $ / MMBtu, and with a sensitivity of +/-23%, the values for the sensitivity analysis are 7,35 $ and 4,60 $ / MMBtu. Although the prices in the sensitivity analysis are named "roof" and "floor" prices, the change in gas prices could turn out to be larger than expected. Exceptionally high gas prices such as the EU natural gas prices in 2022 (Trading Economics, 2024a) could affect results differently than the outcomes in this sensitivity analysis.

The sensitivity analysis finds that increasing the natural gas price by 23% for both the ROW and the European producers causes an increase in fertilizer prices for both markets in all scenarios. Demand reduces accordingly for both markets. Higher gas prices cause a decreased market share for European producers for all scenarios, except for scenario 4 where Norway increases market share by 10%. The strengthened competitiveness is due to larger change in relative costs for foreign gas-dependent industries. Norway, and the EU are exempted from 42% percentage of the cost increase due to this part of production being renewable. Despite the advantage EU production remains 0 in scenario 4, as they are constrained by substantial green hydrogen costs.

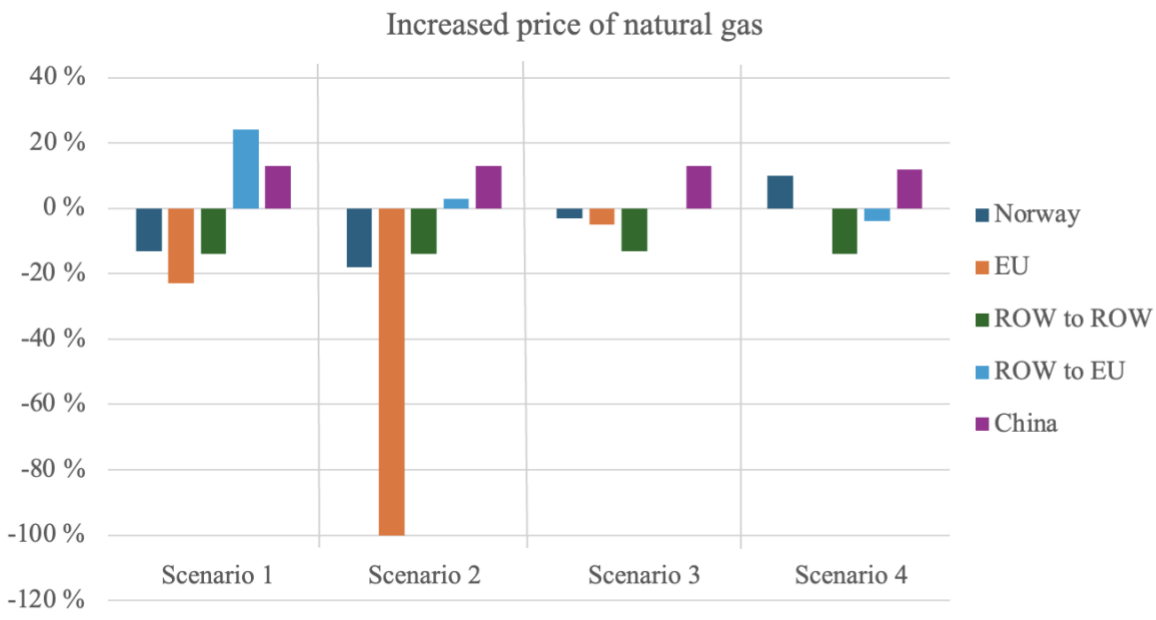

Figure 16: Percentage changes in production from model outputs when natural gas prices increase by 23%.

In all scenarios, when natural gas prices rise, Chinese production increases. This is because coal fertilizer becomes relatively cheaper compared to natural gas-based fertilizer, prompting higher production levels in China. Since Chinese coal-based fertilizer production is highly carbon intensive, emissions from China increase. Despite increased Chinese emission, reduced demand causes global emissions for fertilizer to decrease for all scenarios. In scenario 2, carbon leakage rate increases because of shifts in production from less carbon intensive producers to more carbon intensive factories in China and the ROW. As presented in table 12, higher gas prices in scenario 4 cause a lower carbon leakage rate. This effect is likely due to reduced imports from the ROW to the EU.

Decreasing the natural gas price has the opposite effect on demand, emission, carbon leakage and production for the various producers. All producers but China benefit from lower costs in scenario 3 & 4, except for EU production in scenario 4 where costs are still too large to compete in the market.

Emission in million t CO_2 eq			
	Reference value	Floor price	Roof price
$/MMBtu	**6,5**	**5**	**8**
Scenario 1	473	481	467
Scenario 2	477	484	471
Scenario 3	466	475	459
Scenario 4	472	480	467

Table 11: Total emissions in million tonne CO2 eq from changing the gas prices.

Carbon leakage			
	Reference value	Floor price	Roof price
$/MMBtu	**6,5**	**5**	**8**
Scenario 2	128%	124%	132%
Scenario 4	99%	98%	96%

Table 12: Carbon leakage with various prices of natural gas.

5.6.2 Higher or lower ETS price

The EU ETS price is dependent on many factors, and it is therefore difficult to anticipate the exact price for 2030. If EU climate policies tighten at the same time as the industry struggles to keep up on mitigation initiatives, prices would likely increase due to higher demand for carbon quotas. The technology could also evolve faster than anticipated which would likely decrease prices. The market is also dependent on the industry's expectation for future prices, as well as energy prices (Glushchenko, 2023). These are only some of the factors which cause uncertainty for the ETS price.

In the model the ETS price is based on the average expected ETS price from two different forecasts for 2030. Enerdata's report from 2023 expects a price of 70 € / t CO_2 eq (Cail et al., 2023, p.9) while GMK research center anticipates a higher price of 147 € / t CO_2 eq (Glushchenko, 2023). In the sensitivity analysis, these different expectations are used as inputs to view the effect which ETS price has on model results. Because the CBAM is set based on the ETS price, the CBAM is changed accordingly.

Increasing the ETS price to 147 € / t CO_2 eq decreases production within the EU in scenario 3. Some of this effect is due to reduced demand because of higher prices, while some market share is taken by Norwegian producers which pay a smaller carbon price. Increasing the ETS price has no effect on imports to the EU, which remains 0. Because the EU and ROW market are kept separate due to zero ROW import to the EU, outputs for the ROW market remain unchanged in scenario 3. With increased ETS price Norway takes on some of the EU market share because of lower carbon intensity than the average EU plant.

In scenario 4 Norway increases production by 92% compared to the same scenario in the main model when ETS prices increase. This is because Norway has the lowest carbon intensive production and thus are required to pay relatively less ETS/CBAM costs compared to competitors. Imported EU goods from the ROW decrease because of higher CBAM costs, and the EU production in the same scenario remains unchanged from 0. Despite larger production in Norway, as well as lower ROW production, the global emissions from fertilizer only reduce by less than half a percentage. As seen in table 14 carbon leakage rate for scenario 4 only reduces to 77%, as compared to 99% in the main model. The small decrease in carbon leakage is caused by large increase in production in Norway and a ROW decline in emissions due to loss of market share.

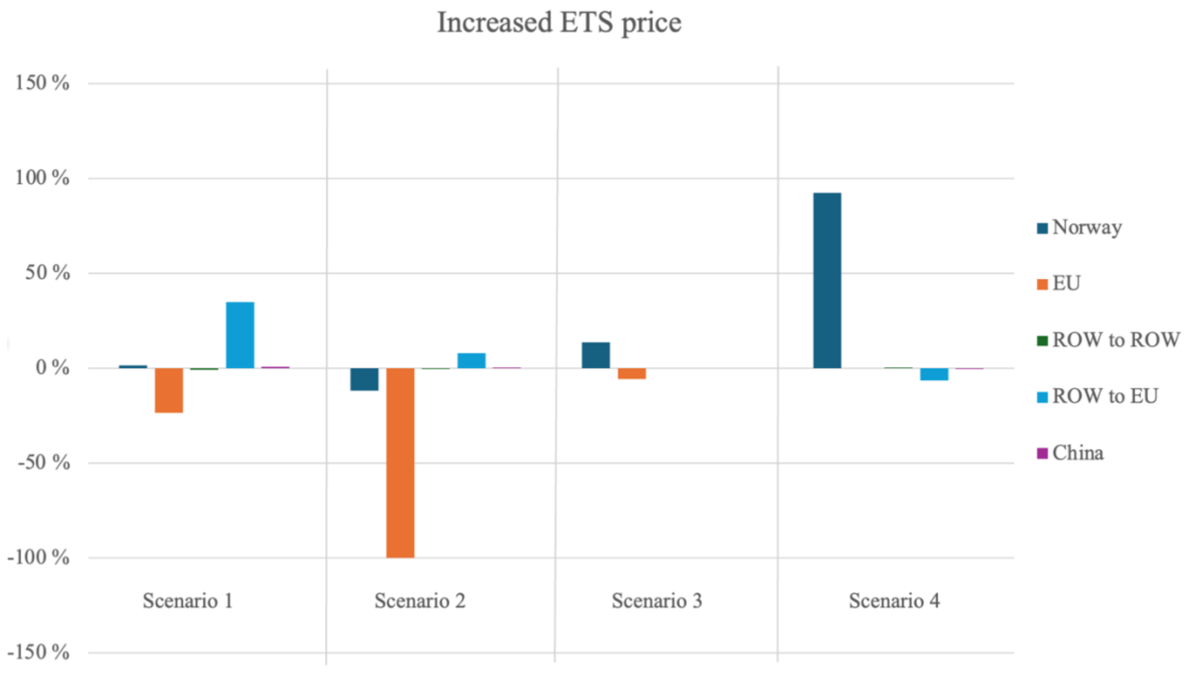

Figure 17: Percentage change in production when ETS price increases to 147 €/ t CO2 eq as compared to a ETS price of 108,5€/ t CO2 eq.

Reducing the ETS prices has little impact in the global fertilizer market simulated in scenario 3. Only the EU market is affected where the EU increases production, while Norway decreases. In scenario 4, EU and Norway produce nothing, while the ROW is the only producer to the EU market. China makes modest gains from a lower ETS price in scenario 4, as they increase production due to ROW exporters being faced with lower tariff costs resulting in increased exports out of the ROW market. In scenario 4 emissions slightly increase globally due to increased production in China and the ROW. Reducing the ETS price therefore causes an increase in leakage, due to larger emissions outside of Europe.

Emission in million t CO_2 eq			
	Reference value	Floor price	Roof price
€ / t CO_2 eq	**108,5**	**70**	**147**
Scenario 1	474	471	474
Scenario 2	477	474	477
Scenario 3	466	467	464
Scenario 4	472	474	470

Table 13: Total emissions from the fertilizer industry when ETS price changes.

Carbon leakage			
	Reference value	Floor price	Roof price
€ / t CO_2 eq	**108,5**	**70**	**147**
Scenario 2	128%	128%	129%
Scenario 4	99%	113%	77%

Table 14: Carbon leakage rate when ETS price changes.

5.6.3 Demand Elasticity

Based on two different research papers as explained in the data (4.6.2) section, the model assumes a demand elasticity of -0,5. In this sensitivity analysis values are taken from a Danish study which finds demand elasticity to be between -0,69 and -0,24 (Hansen, 2004, p.14). The values are replaced as inputs for both markets in the main model, but also in the demand parameters (d^{EU} & d^{ROW}) aggregated from the 2018 data as explained in chapter 4.6.2. When demand changes because of price elasticity, it has various consequences for the market situation in the analysis, which will be further examined in this section.

The impact of demand changes in the analysis varies depending on whether the global market is open or restricted with a CBAM in place. In scenario 2, the global market is open without a CBAM, and the effects from elasticity have the same effect on demand and prices for both markets. In contrast, scenario 3 & 4 show a different pull in demand for the two markets. A more inelastic demand (-0,24) for the two scenarios causes an increase in demand in the EU market, while the ROW decreases demand. Increasing the elasticity to -0,69 decreases demand in the EU because the price is too high relative to the farmers' necessity of the product. The changes occur in the opposite direction for the ROW market, where larger elasticity causes an increase in demand. This effect is likely due to larger available supplies because of decreased imports from the ROW to the EU.

Because demand shifts with a different elasticity input, the emission level also changes accordingly. Increasing the elasticity to -0,69 increases global emissions because of increased demand in the ROW. Decreasing the elasticity to -0,24 has the opposite effect, except for scenario 4 where emissions increase. This is because the suppliers in Europe experience exceptionally high domestic costs in scenario 4. When EU demand increases as a result of more inelastic demand in the same scenario, ROW producers take on nearly all of the new market share, which increases emissions in the ROW. Because the carbon intensive ROW supply increases more than the emission reduction from declining demand in the ROW market, the total emissions also slightly increase.

Emission in million t CO_2 eq			
	Reference value	Floor elasticity	Roof elasticity
Elasticity	**−0,5**	**−0,24**	**−0,69**
Scenario 1	473	468	475
Scenario 2	477	475	478
Scenario 3	466	461	468
Scenario 4	472	473	472

Table 15: Emission when demand elasticity changes.

5.6.4 Higher or lower costs of green technology

Predictions on costs for green hydrogen technologies are limited, and costs may turn out larger or smaller than first anticipated. Subsidies towards 2030 may provide incentive for production and accelerate innovation which may further reduce costs for green hydrogen. The EU has already launched its first green hydrogen auction which will provide 800 € million in subsidies for cost competitive green hydrogen technologies (European Commission, 2023c). Whether or not the EU subsidies will be enough to make green technologies competitive in 2030, is at the current date unknown. In the sensitivity analysis we have therefore both increased and decreased costs of green technologies by 25%, as well as included subsidies to cover 40% of costs to see how outputs in the model are affected. Since RED III is only introduced in scenario 4, it is the only scenario analyzed.

If the price increases by 25% in the sensitivity analysis, it has little effect on the model because the costs are already too high for any EU production. The only change is that the small amount of Norwegian production is replaced by EU imports so that Norwegian production also reduces to zero. Changes for emission and carbon leakage are also minimal.

When green technology costs decrease by 25%, European producers are faced with lower production costs, which increase competitiveness. The EU and Norway therefore increase production by respectively 4 and 0,3 million tonnes of nitrogen. As a result, CBAM makes EU imports from the ROW relatively less competitive, which causes ROW to decrease imports to the EU by 42%. Reducing the price for green technology also causes global emission to decrease by 1,6% as compared to the emissions from the same scenario in the main model (table 16). Even with increased production within Europe, the EU market still achieves emission reductions compared to scenario 1 in the main model. In combination with emission reduction outside of Europe, the reduced technology costs give an overall decrease in carbon leakage (table 17).

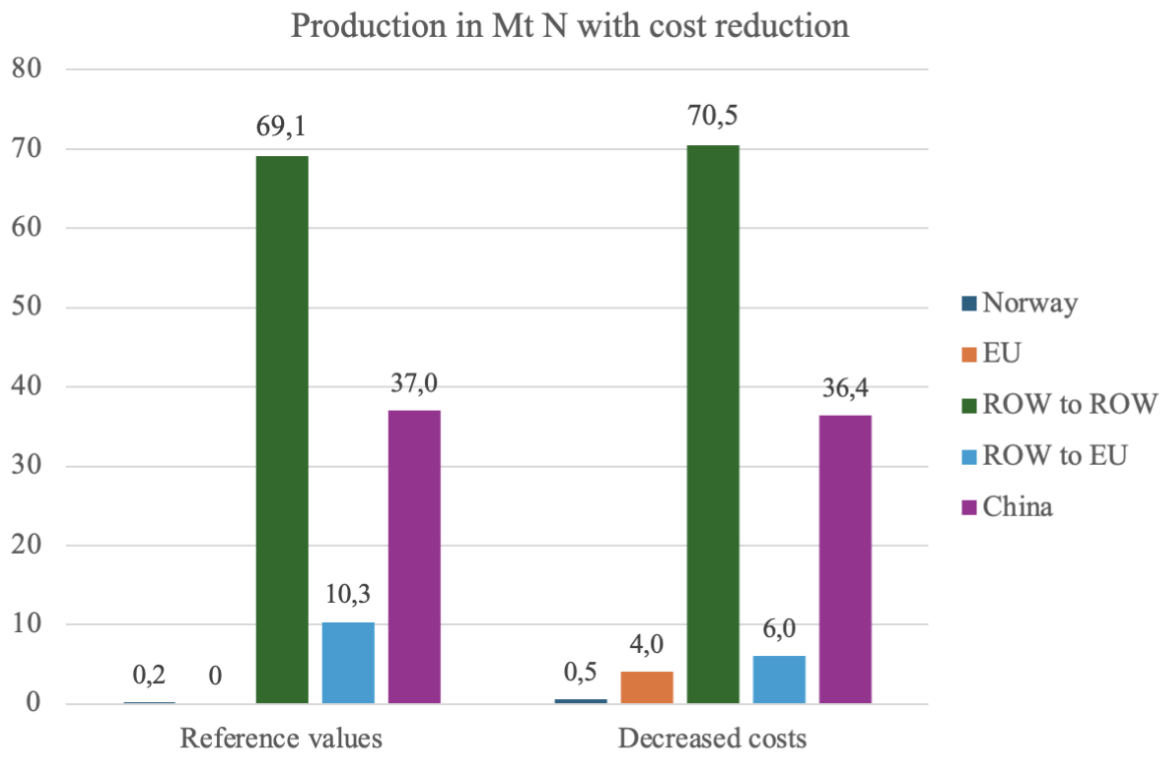

Figure 18: Produced nitrogen fertilizer when costs decrease compared to values from the main model.

If the price further decreases by 40%, as a result of large subsidies, EU and Norway take over larger parts of the EU market and leave imports to the EU to 1,5 million t N. The results from this sensitivity simulation gives the lowest amount of total greenhouse gas emissions, as well as a significant decrease in carbon leakage. The output from this simulation is attractive for European producers but requires significant financial support from EU municipalities.

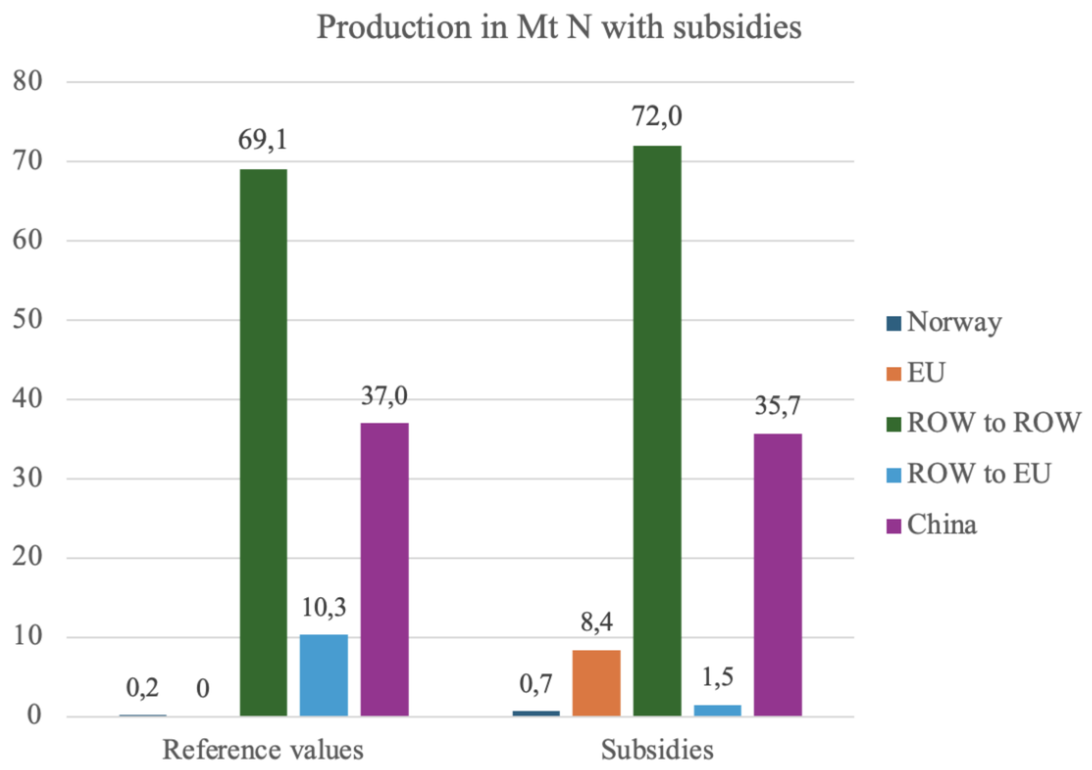

Figure 19: Production of nitrogen fertilizer when introducing subsidies equivalent to 40% of green technology costs.

Emission in million t CO_2 eq				
	Reference value	Subsidy	Decreased price	Increased price
Price change		**−40%**	**−25%**	**25%**
Scenario 4	472	457	465	473

Table 16: Total emissions from the global nitrogen fertilizer industry with different cost levels for green hydrogen technology.

Carbon leakage				
	Reference value	Subsidy	Decreased price	Increased price
Price change		**−40%**	**−25%**	**25%**
Scenario 4	99%	-676%	−3%	96%

Table 17: Carbon leakage from changing the costs for green hydrogen production.

6. Discussion & Limitations

The implications of the results and the potential attractiveness of the scenarios depend on the results from the sensitivity analysis as well as the model design. The evaluation of the policy impact should therefore be viewed in light of the sensitivity of the parameters as well as the model limitations which will be discussed in 6.2 of this chapter.

6.1 Discussion of results

Scenario 2, consisting of reduced free allowances in the ETS with no other climate policy, will cause high carbon leakage and increased global GHG emissions. Furthermore, the results from the same scenario reveal that it will be more expensive for European industry to compete with imports (ROW & China). The sensitivity analysis shows that larger production costs, due to increased natural gas or ETS costs, strengthen this effect. In scenario 3 emissions decrease in areas outside of the EU, which shows that including a CBAM is an effective policy for reducing carbon leakage and overall GHG emissions abroad. These results are supported by previous findings on carbon leakage such as Böhringer et al. (2021), as explained in section 3.5.

In scenario 4, where European production partly relies on green hydrogen, the ROW suppliers experience an exceptionally high boost in market share, due to increased costs for competitors in the EU and Norway. In scenario 4 the sensitivity analysis finds that the results are sensitive to uncertainties in future parameters. When the gas price increases, the gas dependent production, both in Europe, and ROW decreases. The sensitivity analysis also finds that the outcome for Norwegian producers is largely sensitive to the ETS price because of lower carbon intensity. Sensitivity showed that lower ETS costs are poor for Norwegian producers, and that when increasing the ETS price the production increases. A larger ETS price also means a greater CBAM price for foreign EU importers, which is favorable for countries with low emission intensity. When the ETS price increases to 147 € in scenario 4 it is still not large enough for EU production, due to relatively larger carbon intensity and high green technology costs. From the sensitivity analysis it became clear that cost reduction is essential for the competitiveness of green technology and the realization of RED III in the EU. Scenario 4 with 40% lower green technology costs is also the most favorable scenario for reduction of global GHG emissions and carbon leakage.

Further interpretation of results depends on which perspective one has in mind. If the green hydrogen costs remain high according to predictions, scenario 3 is the most beneficial for EU producers, as well as the climate. This is because scenario 3 has the largest market share for EU producers while at the same time being the scenario with the lowest global carbon emissions. Scenario 3 with CBAM is seemingly unproblematic for the EU except for a fertilizer price increase of 28% in the EU. This significant price increase may have consequences for farmers in the EU because fertilizer is an important input for food production. The effect on costs for farmers and potentially also increased food prices may have additional costs and consequences not accounted for in this analysis.

Scenario 3 is also problematic from the point of view of the ROW importers to the EU. Since the CBAM cost is larger for ROW producers due to higher carbon intensity, the policy favors EU production. The decline in market share results in a lower gross revenue for ROW producers, which is a problematic outcome for the producers. As described in the theory chapter 3.5.1, expert opinions also suggest that countries who import to the EU have reasons to oppose the CBAM, which could cause weakened trade relations. It is also possible that foreign countries may respond by choosing to resign from voluntary global climate commitments. The results from scenario 3 suggest that ROW producers to the EU would have reasons to object to the CBAM policy, but the potential effects are not accounted for in the analysis. Further limitations on model design will be accounted for in the next chapter.

6.2 Limitations

The paper takes for granted that free allowances will be reduced according to EU plans and that the CBAM will be implemented according to current design. However, it is worth acknowledging the uncertainty surrounding the development of EU's climate policy, as well as the uncertainty of Norwegian implementation. The CBAM is an adaptive climate policy, and conditions may change significantly towards 2030. It is possible to revise future ambitions based on research and development (R&D), international commitments and political considerations. In the transitional period (2023-2026), described in subchapter 2.1.2, the policy solely works as a monitor and report mechanism for the imported goods. Depending on the observed results from this period CBAM can be changed or adjusted for further development, before being fully implemented by 2034.

The analysis is generated by using a partial equilibrium model, which is based on simplifications of the world economy. The model overlooks the potential impact of the CBAM on other industries, a crucial limitation given that the CBAM policy will extend across six sectors. Neither does the model consider the effect which CBAM may have on ETS-, coal- and gas prices, and instead considers the prices to be exogenous. Since the short-term fertilizer industry is highly dependent on natural gas, and therefore also ETS quotas, it is likely that changes in the fertilizer market would also affect the prices of natural gas and ETS. When considering the CBAM policy altogether, affecting six different highly carbon intensive industries, it is likely that the ETS, coal and gas prices would be affected even more extensively. Since the carbon leakage from the international fossil fuel channel as mentioned in chapter 3.4, is dependent on global fossil fuel prices, it is also possible that carbon leakage from this channel will be affected by changed fossil fuel prices. Fossil fuel prices will also change the supply curves for the gas and coal-fueled power plants. The extent of this effect is not possible to draw from this analysis and would have to be assessed by further research using an extensive general equilibrium model.

In the model, nitrogen fertilizer is treated as a homogeneous good with no trade barriers. However, in reality, nitrogen fertilizer products vary in form and composition in the global market. This means that the model's simplicity assumes all producers offer identical goods, making it easier for farmers to switch between producers. Additionally, the model disregards other trade barriers such as import tariffs and transportation costs, which if included could increase the cost of trading nitrogen fertilizers and result in different prices between countries. These increased trade costs can make it harder for producers to switch between suppliers, potentially leading to a lower carbon leakage rate than indicated by the model. Consequently, given that the model only considers CBAM as a trade barrier, the model output may show different results if other trade restrictions were included.

There is also a question about the feasibility of scenario 4. The result from this scenario shows that costs are so high for 2030 that the EU reduces all production. Nevertheless, if the costs were to go down, there is also a problem of realizing enough infrastructure around production. Today there currently is not enough renewable energy to satisfy the goal for green hydrogen production. Infrastructure is necessary to transport electricity to the plant and to produce hydrogen on sight (Ausfelder, 2022, p.38). Although scenario 4, assumes only green hydrogen will be applied to reach 42% renewable production, RED III opens up for blue hydrogen for some power plants. Blue hydrogen, as detailed in section 2.2.3, refers to natural gas that undergoes a process called carbon capture and storage (CCS). (Erbach & Svensson, 2023, p.2). This kind of technology would lower the costs of reducing emissions, decrease the need for electricity infrastructure and serve as a potential transitional solution in the transitioning phase. Due to potential cost reduction in blue ammonia, including the technology in scenario 4, could potentially make the scenario more attractive for policy makers and industries in the EU and Norway.

Another limitation of the model arises from the extent to which the producers are allowed to reduce emissions from production through technological improvements. Except for scenario 4, where EU producers are required to convert 42% of production to green technology, there is no room for technology improvements. This means that when CBAM is introduced the model assumes that the producers would not have the opportunity to change technology, as result of the increased costs from CBAM. Since the EU producers have taken all the low hanging fruits in reducing emissions in nitrogen fertilizers, the industry argues that fundamental green technology investments are the only means to reduce emissions further (Fertilizers Europe, 2023a). Investing in green technology without government policy is assumed unrealistic in scenario 3 due to extensive costs. If costs were reduced, it could potentially open up for a change to green technology also in scenario 3, but this is outside the boundaries of the model. Future unpredictability in technological change also causes uncertainty in the cost parameters in all supply functions.

Since the ROW have not yet realized the low hanging technology changes already achieved by the EU, it is also likely that these may be accomplished by the ROW producers in the short term. With reduced CBAM costs as an incentive these technology improvements may potentially make the ROW supply more attractive in the EU market. This possibility of cheap technology improvement in the short run for ROW producers is not accounted for in the model, and is a significant limitation that should be considered when interpreting the model results.

In addition to the lack of model opportunity for technology improvements, the model also assumes the EU is the only country with an emissions trading system and other policies for green fertilizer production in 2030. This assumption is made due to simplicity reasons, and does not reflect the predicted world landscape of green technology policies. 196 countries have committed to prevent climate change through the Paris agreement (UNFCCC, n.d), but the extent which green policies are to be realized in 2030 is uncertain. Based on country specific initiatives such as the IRA in the USA and Indias plans for implementing a carbon trading system in 2025 (Singh, 2023), there is reason to believe in a more extensive carbon emission policies also outside the EU in 2030. An example of the potential unknown effect of including ROW green policies in the model could be associated with the extent of carbon trading system in the ROW. If the carbon trading system in the ROW increases demand for green ammonia, which is cheaper within the EU, the EU could potentially end up in a situation of net export. Another potential effect could be that the ROW speed up green technology transition faster than Europe. which would pull in the opposite direction where EU industry instead outsources production. Since the ROW green policies are not accounted for in the model, it could change the model outcomes depending on the magnitude of the policies.

In the model the EU producers can only produce to the EU market and are not permitted to export to the ROW. This simplification is based on the EU being a net importing region. Because the EU in the model does not export, it makes the ETS export rebate dilemma mentioned in chapter 3.5.2 less problematic. In reality there are however differentialized nitrogen goods, which incentivize some EU export. Since the goods are not differentialized in the model, the potential effect from lack of rebates on carbon leakage and the EU export industry, can therefore not be drawn from this paper. Lack of export rebates could also be a problem for the EU industry if the market situation suddenly becomes different in 2030, and the EU becomes net exporters due to increased ROW demand. The absence of export rebates could then potentially harm the EU export industry and increase carbon leakage. This is outside the scope of the model, but could potentially be interesting to look at for further research.

7. Conclusion

The European Union (EU) has decided, in the "Fit for 55" package, to introduce a carbon tariff as an additional mechanism in the EU Emission Trading System (ETS) when phasing out free allowances. The Carbon Border Adjustment Mechanism (CBAM) implies that companies importing goods to the EU from carbon intensive sectors must pay a tariff that reflects the carbon content of this good. This tariff will gradually be applied to EU's trade market in the beginning of 2026, and aims to reduce the risk of carbon leakage, safeguard domestic competitiveness, while fostering global climate cooperation.

The thesis has provided an overview of the EU's climate policy of implementing CBAM on the nitrogen fertilizer market. We applied different scenarios to an ex ante model based on EU ambitions for out-phasing of free allowances in the EU ETS, the in-phasing of CBAM, and the potential effect of combining CBAM with policy for green technology transition in Renewable Energy Directive III (RED III). Throughout the paper we have analyzed the effects of the policies on industry competitiveness, carbon leakage and global greenhouse gas (GHG) emissions.

When phasing out EU free allowances to 51,5% without introducing a CBAM (scenario 2) we found a large market loss for the EU industry. Since EU and Norwegian producers are faced with increased costs, they are less competitive compared to Rest of the World (ROW) imports to the EU. As a result, ROW imports to the EU market increase by 135% as compared to the current policy situation (scenario 1). This causes a shift to a more carbon intensive production in the ROW which causes significant carbon leakage and rise in global emissions. Since the phasing out of free allowances results in a great reduction in EU competitiveness as well as increased emissions, it is clear from the analysis that it is not an advantageous policy on its own. If the EU wishes to decrease emissions while at the same time protecting domestic fertilizer industry, other mechanisms are needed.

In the next scenario (scenario 3) we introduced CBAM as a potential mechanism for reducing carbon leakage and leveling the playing field in the EU market. Because the CBAM cost is based on the actual carbon intensity from production, the ROW importers to the EU pay a significant carbon price. The cost reduces all incentives for the ROW to engage in the EU market, and the policy therefore proves favorable for EU producers. Because EU and Norway both increase market share when CBAM is introduced, they also increase emissions as compared to current policy. Despite the increase in domestic emissions, the global emissions from fertilizers slightly decrease by 1,5%. The CBAM policy therefore proves effective for protecting EU industry and reducing the negative effects from carbon leakage, but since the scenario does not allow for technological development, the reduction in emissions is modest. Lastly the analysis considered the effect of combining CBAM with a planned EU policy for transitioning to green hydrogen production, called RED III. The RED III requires EU producers to convert 42% of their production to green technology solutions. Combining the policies results in significant cost increase for the European producers, so that EU production reduces to nothing. The emissions remain unchanged, and the carbon leakage increase compared to a situation with current policy. The outcome of the analysis is especially sensitive to changes in costs, where a potential decrease in green hydrogen costs could raise EU market share. If costs decrease by 40% because of technological development or subsidies, it significantly increases EU competitiveness and contributes positively to addressing carbon leakage and emission reduction.

For further research it would be interesting to look into the effect of technological development also outside the EU. It is likely that the ROW will increase ambition level toward 2030, and looking into combining CBAM with external climate policies outside the EU, such as the IRA, could be an interesting supplement to this analysis. Another potential aspect could be to combine CBAM for the fertilizer industry with other industries through a general equilibrium model. Looking at the effect on the whole economy could provide holistic insight to the CBAM policy, and may also provide additional information on the potential leakage through the fossil fuel channel.

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Annex

1. Results - Model Variables

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Price EU Market	464,8	474,3	594,9	646,7
Price ROW Market	464,8	474,3	457,7	473,3
Demand EU	12,4	12,3	11,0	10,5
Demand ROW	107,1	106,0	107,9	106,1
Supply Norway	0,6	0,5	0,9	0,2
Supply EU	7,2	0,8	10,1	0
Supply ROW to ROW	70,9	68,9	72,5	69,1
Supply ROW to EU	4,7	11,0	0	10,3
Supply China	36,2	37,1	35,5	37,0

2. Results - Main Model Revenue

Revenue in M €				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Norway	274	218	536	131
EU	3326	403	5991	0
China	16802	17600	16227	17516
ROW	35135	37885	33164	39384

Change in Revenue					
Scenario 2 Revenue		Scenario 3 Revenue		Scenario 4 Revenue	
Total change in revenue M €	Percentage change in revenue	Total change in revenue M €	Percentage change in revenue	Total change in revenue M €	Percentage change in revenue
−2923	−88%	2665	80%	−3326	−100%
−56	−20%	261	95%	−143	−52%
797	5%	−575	−3%	713	4%
2750	8%	−1971	−6%	4249	12%

3. Results -Main Model Policy Costs

Scenario 1			
	ETS-/ CBAM cost in € / t N	ETS costs M €	ETS costs/ revenue
EU	68	488	15%
Norway	0	0	0%
Scenario 2			
EU	160	136	34%
Norway	45	21	10%
Scenario 3			
EU	160	1614	27%
Norway	45	41	8%
China	331	0	-
ROW	216	0	-

Scenario 4 Costs for RED & ETS/ CBAM					
	ETS-/ CBAM cost in € / t N	Total ETS/ CBAM costs M €	Green technology cost € / t N	Total cost of green technology M €	Total green policy cost/ gross revenue
EU	93	0	425	0	-
Norway	26	5	389	79	64%
China	331	0	0	0	0%
ROW to EU	216	2227	0	0	33%

4. Results -Main Model Emissions

GHG Emissions M tonne CO_2 eq				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	17,0	2,0	23,9	0
Norway	0,8	0,6	1,2	0,2
China	207,5	213,0	203,5	212,4
ROW	247,2	261,2	236,9	259,7
Total	472,5	476,8	465,5	472,3

5. Results - Main Model Carbon Leakage

Scenario 2			
	Carbon Intensity	Change in output	Carbon emission change
EU	2,4	−6,3	−15,0
Norway	1,3	−0,1	−0,2
China	5,7	1,0	5,5
ROW to ROW	3,3	−2,0	−6,7
ROW to EU	3,3	6,3	20,6
Carbon leakage		128%	

Scenario 4			
Change in output	Change in avoided emissions from decreased demand	Avoided emission from green tech	Carbon emission change
−7,2	−17,0	0	−17,0
−0,4	−0,5	−0,1	−0,6
0,9	4,9	0	4,9
−1,8	−6,0	0	−6,0
5,7	18,5	0	18,5
Carbon leakage		99%	

6. Sensitivity Analysis

6.1 Sensitivity: Gas price

Production in million t N				
		Reference value	**Floor price**	**Roof price**
$ / MMBtu		**6,5**	**5**	**8**
Scenario 1				
	Price EU Market	464,8	417,7	513,1
	Price ROW Market	464,8	417,7	513,1
	Demand EU	12,4	13,1	11,8
	Demand ROW	107,1	113,0	101,9
	Supply Norway	0,6	0,7	0,5
	Supply EU	7,2	8,9	5,5
	Supply ROW to ROW	70,9	81,5	60,9
	Supply ROW to EU	4,7	3,5	5,8
	Supply China	36,2	31,5	41,0
Scenario 2				
	Price EU Market	474,3	427,0	521,7
	Price ROW Market	474,3	427,0	521,7
	Demand EU	12,3	12,9	11,7
	Demand ROW	106,0	111,7	101,1
	Supply Norway	0,5	0,5	0,4
	Supply EU	0,8	2,6	0
	Supply ROW to ROW	68,9	79,3	59,2

	Supply ROW to EU	11,0	9,8	11,3
	Supply China	37,1	32,4	41,8
Scenario 3				
	Price EU Market	594,9	532,8	658,1
	Price ROW Market	457,7	412,5	504,2
	Demand EU	11,0	11,6	10,4
	Demand ROW	107,9	113,7	102,8
	Supply Norway	0,9	0,9	0,9
	Supply EU	10,1	10,7	9,6
	Supply ROW to ROW	72,5	82,7	62,7
	Supply ROW to EU	0	0	0
	Supply China	35,5	31,0	40,1
Scenario 4				
	Price EU Market	646,7	601,7	693,0
	Price ROW Market	473,3	428,3	519,6
	Demand EU	10,5	10,9	10,2
	Demand ROW	106,1	111,6	101,3
	Supply Norway	0,2	0,2	0,2
	Supply EU	0	0	0
	Supply ROW to ROW	69,1	79,0	59,7
	Supply ROW to EU	10,3	10,7	9,9

	Supply China	37,0	32,5	41,6

Emissions EU gas 8 $ M t CO_2 eq				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	13,1	0	22,7	0
Norway	0,7	0,5	1,2	0,2
China	235,1	240,0	230,0	238,8
ROW	218,2	230,8	205,2	227,6
Total	467,1	471,4	459,1	466,6

Emission EU gas 5 $ M t CO_2 eq				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	21,2	6,1	25,4	0
Norway	0,9	0,7	1,2	0,1
China	180,6	185,9	177,7	186,7
ROW	278,0	291,6	270,5	293,5
Total	480,7	484,3	474,7	480,3

Carbon leakage			
	Reference value	Floor price	Roof price
$ / MMBtu	6,5	5	8
Scenario 2	128%	124%	132%
Scenario 4	99%	98%	96%

6.2 Sensitivity: ETS price

Production in million t N				
		Reference value	**Floor price**	**Roof price**
	€ / t CO_2 eq	**108,5**	**70**	**147**
Scenario 1				
	Price EU Market	464,8	462,3	467,2
	Price ROW Market	464,8	462,3	467,2
	Demand EU	12,4	12,4	12,4
	Demand ROW	107,1	107,4	106,8
	Supply Norway	0,6	0,6	0,6
	Supply EU	7,2	8,8	5,5
	Supply ROW to ROW	70,9	71,5	70,4
	Supply ROW to EU	4,7	3,0	6,3
	Supply China	36,2	35,9	36,4
Scenario 2				
	Price EU Market	474,3	468,5	475,7
	Price ROW Market	474,3	468,5	475,7
	Demand EU	12,3	12,4	12,3
	Demand ROW	106,0	106,7	105,8
	Supply Norway	0,5	0,5	0,4
	Supply EU	0,8	4,8	0,0
	Supply ROW to ROW	68,9	70,1	68,6

	Supply ROW to EU	11,0	7,1	11,9
	Supply China	37,1	36,5	37,2
Scenario 3				
	Price EU Market	594,9	545,9	644,5
	Price ROW Market	457,7	457,7	457,7
	Demand EU	11,0	11,5	10,5
	Demand ROW	107,9	107,9	107,9
	Supply Norway	0,9	0,8	1,0
	Supply EU	10,1	10,7	9,5
	Supply ROW to ROW	72,5	72,5	72,5
	Supply ROW to EU	0	0	0
	Supply China	35,5	35,5	35,5
Scenario 4				
	Price EU Market	646,7	586,3	707,3
	Price ROW Market	473,3	474,4	472,4
	Demand EU	10,5	11,1	10,1
	Demand ROW	106,1	106,0	106,2
	Supply Norway	0,2	0	0,4
	Supply EU	0	0	0
	Supply ROW to ROW	69,1	68,9	69,3
	Supply ROW to EU	10,3	11,0	9,7

	Supply China	37,0	37,1	36,9

Emissions ETS price 147 € / t CO_2 eq
M t CO_2 eq

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	13,1	0	22,6	0
Norway	0,8	0,5	1,3	0,3
China	208,9	213,7	203,5	211,8
ROW	250,8	263,1	236,9	258,3
Total	473,5	477,4	464,4	470,4

Emissions 70 € / t CO_2 eq
M t CO_2 eq

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	21,0	11,3	25,4	0
Norway	0,8	0,7	1,0	0
China	206,1	209,6	203,5	213,0
ROW	243,6	252,6	236,9	261,3
Total	471,5	474,2	466,8	474,3

Carbon leakage

	Reference value	Floor price	Roof price
€ / t CO_2 eq	108,5	70	147
Scenario 2	128%	128%	129%
Scenario 4	99%	113%	77%

6.3 Sensitivity: Demand elasticity

Production in million t N				
		Model	**Floor elasticity**	**Roof elasticity**
	Elasticity	**−0,5**	**−0,2**	**−0,7**
Scenario 1				
	Price EU Market	464,8	462,8	466,0
	Price ROW Market	464,8	462,8	466,0
	Demand EU	12,4	12,3	12,5
	Demand ROW	107,1	106,0	107,8
	Supply Norway	0,6	0,6	0,6
	Supply EU	7,2	7,0	7,3
	Supply ROW to ROW	70,9	70,0	71,5
	Supply ROW to EU	4,7	4,7	4,6
	Supply China	36,2	36,0	36,3
Scenario 2				
	Price EU Market	474,3	474,4	475,0
	Price ROW Market	474,3	474,4	475,0
	Demand EU	12,3	12,2	12,3
	Demand ROW	106,0	105,3	106,4
	Supply Norway	0,5	0,5	0,5
	Supply EU	0,8	0,1	0,9
	Supply ROW	68,9	68,2	69,2

	to ROW			
	Supply ROW to EU	11,0	11,7	11,0
	Supply China	37,1	37,1	37,2
Scenario 3				
	Price EU Market	594,9	601,9	590,4
	Price ROW Market	457,7	455,0	459,5
	Demand EU	11,0	11,5	10,6
	Demand ROW	107,9	106,4	108,8
	Supply Norway	0,9	0,9	0,9
	Supply EU	10,1	10,6	9,7
	Supply ROW to ROW	72,5	71,2	73,2
	Supply ROW to EU	0	0	0
	Supply China	35,5	35,2	35,6
Scenario 4				
	Price EU Market	646,7	646,9	646,7
	Price ROW Market	473,3	473,5	473,3
	Demand EU	10,5	11,3	10,0
	Demand ROW	106,1	105,4	106,6
	Supply Norway	0,2	0,2	0,2
	Supply EU	0	0	0
	Supply ROW to ROW	69,1	68,4	69,6

	Supply ROW to EU	10,3	11,1	9,8
	Supply China	37,0	37,0	37,0

Emissions Elasticity -0,24 M t CO_2 eq				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	16,7	0,2	25,2	0
Norway	0,8	0,6	1,2	0,2
China	206,4	213,0	201,9	212,5
ROW	244,3	261,3	232,9	260,0
Total	468,1	475,1	461,3	472,6

Emission Elasticity -0,69 M t CO_2 eq				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EU	17,2	2,1	23,1	0
Norway	0,8	0,6	1,2	0,2
China	208,2	213,4	204,5	212,4
ROW	249,0	262,1	239,4	259,6
Total	475,3	478,3	468,2	472,2

Carbon leakage			
	Reference value	Floor elasticity	Roof elasticity
Elasticity	**−0,5**	**−0,24**	**−0,69**
Scenario 2	128%	142%	120%
Scenario 4	99%	126%	83%

6.4 Sensitivity: Cost of green technology

Scenario 4: Production in million t N				
	Reference value	**Subsidy**	**Decreased price**	**Increased price**
Price change		**40%**	**−25%**	**25%**
Price EU Market	646,7	633,4	640,2	647,0
Price ROW Market	473,3	460,0	466,8	473,6
Demand EU	10,5	10,6	10,6	10,5
Demand ROW	106,1	107,6	106,8	106,1
Supply Norway	0,2	0,7	0,5	0
Supply EU	0	8,4	4,0	0
Supply ROW to ROW	69,1	72,0	70,5	69,0
Supply ROW to EU	10,3	1,5	6,0	10,5
Supply China	37,0	35,7	36,4	37,0

Scenario 4: Emission			
	Subsidy	**Decreased price**	**Increased price**
	40%	**−25%**	**25%**
EU	11,6	5,6	0
Norway	0,6	0,4	0
China	204,8	208,7	212,6
ROW	240,3	250,2	260,2
Total	457,2	464,8	472,7

Carbon leakage				
	Reference value	Subsidy	Decreased price	Increased price
Price change		**−40%**	**−25%**	**25%**
Scenario 4	99%	-676%	−3%	96%

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