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MINA

# Voluntary Carbon Credits as an Incentive to Capture and Store Biogenic Emissions at Waste Incineration Plants

## A Profitability Assessment of Future Investment in Carbon Capture and Storage at Waste Incineration Plants, Based on a Separate Market Analysis of the Voluntary Carbon Market Post-2030

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## Acknowledgements

This thesis marks my completion of a master's program in Renewable Energy at the Norwegian University of Life Sciences. Six wonderful years at Agrarmetropolen are coming to an end.

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Finally, I would like to thank family and friends who always cheer from the sideline – I would not have been able to accomplish this without you <3

Before I wrap my bag I have a few last words, keep smiling and capture…

...**C**ARBON

...L**A**TE NIGHTS

...SU**P**ERFRIENDS

...A LO**T** OF REDBULL AND CANDYKING

...SAMF**U**NNET I ÅS

... **R**ENEWABLE ENERGY

...TH**E** FUTURE

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Ås, 15. May 2022

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# Abstract

To reach the goal of The Paris Agreement the transition to renewable energy and energy efficiency will be necessary, but insufficient to achieve the goal of 1,5 Degree Celsius. According to the UN's Climate Panel and IEA, we will have to make greater use of removal projects and create negative emissions. The potential in the waste industry is great both for cutting emissions and creating negative emissions. Captured biogenic $CO_2$ creates negative emissions and about 50 percent of the emissions from waste incineration plants are biogenic. Carbon Capture and Storage (CCS) requires significant investments and is currently unprofitable in the waste industry. However, captured biogenic $CO_2$ qualifies for the sale of carbon credits on the Voluntary Carbon Market (VCM). The VCM is an immature and small market. As the situation is today, it is difficult for companies to know whether the sale of such credits can make an investment in carbon capture and storage profitable or not.

This thesis addresses the challenging of high costs and lack of incentives related to CCS at waste incinerations plants. I examine whether the sale of voluntary carbon credits can be a good enough incentive to make CCS of biogenic emissions profitable for waste incineration plants by 2030.

The main findings in the market analysis indicate that the VCM will grow in the years towards and after 2030, both in quantitates and prices. For a well-functioning VCM, integrity must be ensured in the marked. The most important factors to achieve this are: a heterogeneous market, avoided double counting, additionality, and a standard for verification.

I find that the sale of voluntary carbon credits from the biogenic emissions can lead to profitability in investing of CCS at waste incineration plants. This requires that the prices in the VCM are set high enough. Lower prices in the VCM can be accepted if waste incineration is included in the EU ETS. I observe that the project of CCS at waste incineration is most sensitive to changes in operation and maintenance cost, saved costs, carbon credit prices and the share of biogenic emissions in the waste mix. The sensitivity analyzes indicate that the project is quite robust to changes.

## Sammendrag

For å nå målet i Parisavtalen vil overgangen til fornybar energi og energieffektivisering være nødvendig, men ikke tilstrekkelig for å nå målet om 1,5 grader celsius. Ifølge FNs klimapanel og IEA må vi i større grad benytte fjerningsprosjekter og skape negative utslipp. Potensialet i avfallsbransjen er stort både for å kutte utslipp og å skape negative utslipp. Fanget $CO_2$ med biogent opprinnelse skaper negative utslipp og omtrent 50 prosent av utslippene fra avfallsforbrenning er biogene. Karbonfangst- og lagring (CCS) krever betydelige investeringer og er i dag ulønnsomt i avfallsindustrien. Fanget biogent $CO_2$ kvalifiseres for salg av karbonkreditter på det frivillige karbonmarkedet (VCM). VCM er et umodent og lite marked. Slik situasjonen er i dag, er det vanskelig for bedrifter å vite om salg av slik kreditter kan gjøre investering i CCS lønnsomt eller ikke.

Denne oppgaven tar for seg utfordringen knyttet til høye kostnader og mangel på insentiver knyttet til CCS ved avfallsforbrenningsanlegg. Jeg undersøker om salg av frivillige karbonkreditter kan være et godt nok insentiv til å gjøre CCS av biogene utslipp lønnsomt for avfallsforbrenningsanlegg i 2030.

Hovedfunnene i markedsanalysen viser at VCM vil vokse i årene frem mot og etter 2030. For et velfungerende VCM kreves det integritet i markedet. De viktigste faktorene for å oppnå dette er: et heterogent marked, unngå dobbelttelling, addisjonalitet og en felles standard for verifisering.

Lønnsomhetsanalysene viser at salg av frivillige karbonkreditter fra de biogene utslippene kan føre til lønnsomhet ved investering i CCS ved avfallsforbrenningsanlegg. Dette krever at prisene i VCM settes høyt nok. Lavere priser i VCM kan aksepteres dersom avfallsforbrenning er inkludert i EU ETS. Jeg observerer at prosjektet er mest følsomt for endringer i drifts- og vedlikeholdskostnader, sparte kostnader, karbonkredittpriser og andelen biogene utslipp i avfallsblandingen. Sensitivitetsanalysene indikerer at prosjektet er ganske sterkt overfor endringer.

# Abbreviations

**BECCS:** Bioenergy with carbon capture and storage

**Bio-CCS:** Ways to capture and store $CO_2$ from the natural carbon cycle

**CAPM:** The Capital Asset Pricing Modell

**CCS:** Carbon capture and storage

**CDM:** Clean Development Mechanism

**$CO_2$:** Carbon Dioxide

**$CO_2e$:** Carbon Dioxide Equivalents

**COP:** Conference of the Parties

**DACCS:** Direct Air Carbon Capture and Storage

**EU ETS:** The EU emission trading system

**IRR:** Internal Rate of Return

**LCOC:** Levelized Cost of Carbon Capture and Storage

**MSR:** Market Stability Reserve

**VCM:** Voluntary carbon market

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# 1. Introduction

To reach the goal of The Paris Agreement, the transition to renewable energy and energy efficiency will be necessary but insufficient to achieve the goal of 1,5 degrees Celsius. According to the UN's Climate Panel and IEA, we will have to make greater use of removal projects and create negative emissions (Bouckaert et al., 2021; Masson-Delmotte et al., 2018). Negative emissions mean permanent or long-term biogenic carbon capture and storage (CCS) or direct air capture and storage (DACCS) and are often called carbon removal (Torvanger, 2021). The definition of biogenic CCS includes both engineered and natural ways to capture and store $CO_2$ from the natural carbon cycle. It can be nature-based projects such as reforestation or engineered-based technologies such as capture and storage (Onarheim & Arasto, 2018).

## 1.1 Motivation and Purpose

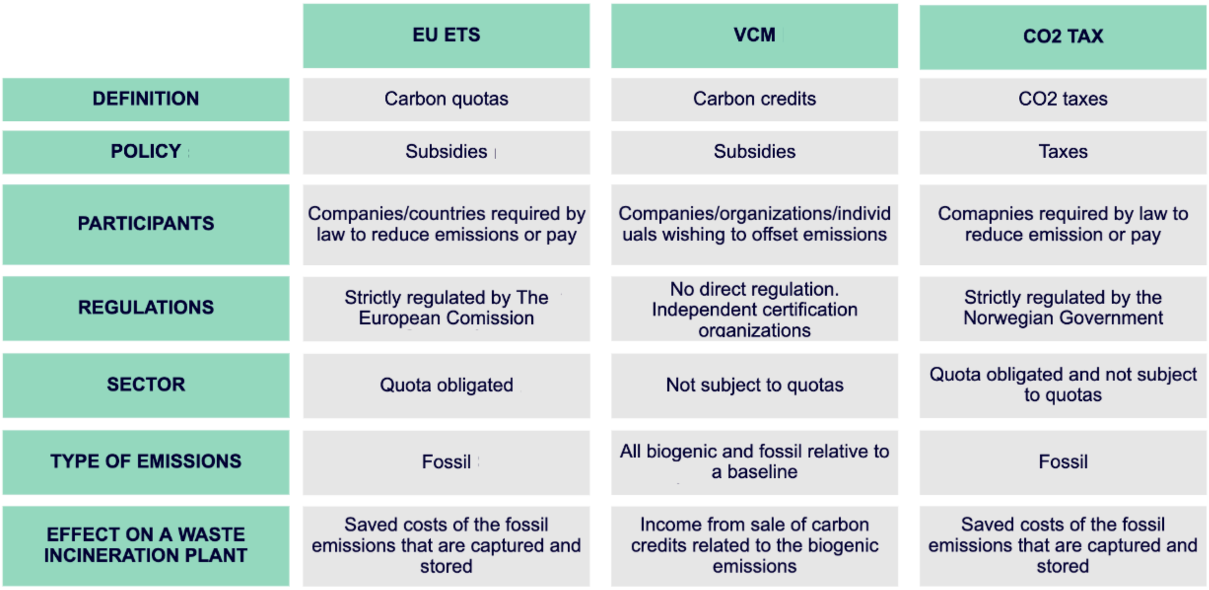
It is estimated that approximately 50 percent of emissions from waste incineration are biogenic (Torvanger, 2021; Zero, 2022). Emissions from the waste industry account for 3.5 percent of the greenhouse gas emissions in Norway (Miljødirektoratet, 2021a). This is approximately 0,9 $MtCO_2$ each year (Zero, 2022). Those numbers include only fossil emissions. Since emissions of biogenic origin are considered a part of the natural carbon cycle, they do not count in the Norwegian greenhouse gas account (Miljødirektoratet, 2021a). It is crucial that the waste sector takes actions of their emissions, both the biogenic and fossil parts (Kearns, 2019). However, to achieve negative emissions, which the UN´s Climate Panel finds crucial, there must be a system for the biogenic emissions. The potential in the waste industry is great both for cutting emissions and creating negative emissions. Zero estimates that CCS must be implemented at waste incineration plants in Norway to achieve the emission target by 2030 (Zero, 2022).

In 2021, the Norwegian Government introduced a $CO_2$ tax on waste incineration aiming to give the waste industry an incentive to invest in CCS.  This tax only includes the fossil parts of the emissions and provides a weaker incentive for capturing the biogenic emissions. In 2022, this tax is 196 NOK/$tCO_2$ , which means a price of only 98 NOK/$tCO_2$ at a waste incineration plant. The waste industry is yet not included in the EU Emission Trading System (ETS) and therefore incurs no additional cost than. Without financial support or incentives, it is unlikely that CCS will be profitable in the waste industry by 2030 (Meld. St. 13 (2020-2021)). Nevertheless, a new proposal from the EU establishes that the fossil part of the emissions from waste incineration should be a part of the EU ETS by 2028 (European Commission, 2021b).

The Voluntary Carbon Market (VCM) is a carbon market that operates outside the regulated markets and is based on voluntariness. This allows companies to become emission-neutral or emission-negative by buying voluntary carbon credits. A voluntary carbon credit is bought for either each ton of fossil $CO_2$ reduced or avoided compared to a baseline in the non-quota sector or for each ton of biogenic $CO_2$ removed from the natural carbon cycle (Ecosystem Marketplace, n.a.; Mazzochi et al., 2021). This means that about half of the captured emissions at waste incineration plants qualify for the sale of voluntary carbon credits. This creates opportunities for income that can help make investing in CCS profitable at a waste incineration plant.

Taskforce on Scaling Voluntary Carbon Markets (TSVCM) believes that a well-functioning VCM is crucial for financing necessary avoidance, reduction, and removal projects (TSVCM, 2021). McKinsey Sustainability estimates that a well-functioning VCM could lead to trillions of dollars being spread to projects like CCS at waste incineration plants (Blaufelder et al., 2021). The VCM is nevertheless an immature and small market. As the situation is today, it is difficult for companies to know whether the sale of such credits can make an investment in CCS profitable or not. Table 1 shows the main factors that separate the various instruments motivating emissions reductions that apply to waste incineration plants and which emissions they cover. The elements in the table will be explained throughout the thesis, and the table is only intended as an overall picture for further understanding of the thesis.

*Table 1: Summarize of the main elements motivation to emission reductions at a waste incineration plant*



| | **EU ETS** | **VCM** | **CO2 TAX** |
|---|---|---|---|
| **DEFINITION** | Carbon quotas | Carbon credits | CO2 taxes |
| **POLICY** | Subsidies | Subsidies | Taxes |
| **PARTICIPANTS** | Companies/countries required by law to reduce emissions or pay | Companies/organizations/individuals wishing to offset emissions | Comapnies required by law to reduce emission or pay |
| **REGULATIONS** | Strictly regulated by The European Comission | No direct regulation. Independent certification organizations | Strictly regulated by the Norwegian Government |
| **SECTOR** | Quota obligated | Not subject to quotas | Quota obligated and not subject to quotas |
| **TYPE OF EMISSIONS** | Fossil | All biogenic and fossil relative to a baseline | Fossil |
| **EFFECT ON A WASTE INCINERATION PLANT** | Saved costs of the fossil emissions that are captured and stored | Income from sale of carbon credits related to the biogenic emissions | Saved costs of the fossil emissions that are captured and stored |

## 1.2 Research questions

This study aims to answer the following main research question:

- *Can income from the sale of voluntary carbon credits for biogenic emissions ensure profitability in the investment of carbon capture and storage projects at waste incineration plants?*

Furthermore, the following sub-questions will be examined to find an answer to the main research question:

1. *How will the voluntary carbon market and the prices and quantities of the carbon credits traded there develop towards and after 2030?*
2. *Will it be profitable for a waste incineration plant to invest in carbon capture and storage based on income from carbon credits origin from capturing the biogenic emissions?*

A market analysis of the VCM is conducted to map the future demand, supply, and prices in the VCM (sub-question 1). A minor study of the EU ETS is also performed to examine the connection with the VCM and how it will affect the waste industry. Then the result from the marked analysis will be used in a profitability assessment of CSS at a waste incineration plant (sub-question 2).

## 1.3 Outline

The thesis is structured as follows. First, I did a literature review to see what kind of literature exists based on the two sub-questions in chapter 2. The background for the thesis, and essential basic principles, are then described and explained in chapter 3. chapter 4 describes the methods and theory used in the thesis. chapter 5 presents the market analysis (sub-question 1) and then the profitability analysis of CCS at a waste incineration plant (sub-question 2). In chapter 6, the results are discussed in light of the sub-questions. I will present and discuss the main findings of the results in chapter 7. The limitations of my research methods and data will also be commented on in this part. chapter 7 concludes the thesis and suggests further research.

What is common in this thesis is that all the chapters are divided into two parts, where I analyze sub-question 1 and then sub-question 2. The answers I find after the analysis in sub-question 1 are used to answer parts of sub-question 2.

# 2 Literature Review

In this chapter, I reviewed literature relevant to the research question of this thesis. My approach was as follows. Firstly, I searched for literature that covers the future of the voluntary carbon market (sub-question 1). Secondly, I searched for literature that says something about the profitability of CCS at waste incineration plants (sub-question 2).

## 2.1 Future of the voluntary carbon market

According to Trove Research (2021), the VCM only accounted for 0,2 percent of total global emissions in 2020. This is after the market has almost tripled in the last three years pre 2021 (Streck, 2021). This says something about how small the market is and has been. Regardless of the size, Streck argues that the market has great potential to contribute to the creation of negative emissions. The market has the opportunity to grow much larger, but this requires stricter rules so that the VCM does not lead to greenwashing and undermining the goals of the Paris agreement. The growing interest and demand from companies that want to become net-zero is a unique opportunity to develop the market (Streck, 2021). From a quantity of 95 $MtCO_2e$ per year in 2020, Trove Research believes demand can reach between 340-510 $MtCO_2$ per year by 2030 (Trove Research et al., 2021). A well-functioning VCM can contribute to from significant environmental benefits (Streck, 2021).

Kreibich and Hermwille point out that the growing expectations from companies do not match the many challenges in the VCM (Kreibich & Hermwille, 2021). Their analyzes indicate that many companies want to use carbon credits to become net-zero emitters. The demand is there; the problem is just to put in place a standard regulation that ensures credibility in the market and projects that actually create negative emissions. If demand increases too much before this happens, it will lead to greenwashing. The integrity of the market will be destroyed (Kreibich & Hermwille, 2021). Although VCM has many weaknesses, Cornille et al. (2021) believe it is possible to give the market a new and better life. The development in the market is positive, and the potential is there, but there is still a long way to go, considering the current market structure (Cornillie et al., 2021).

A report by Rosales et al. (2021) concluded that a well-functioning VCM, with the help of other policy instruments, will lead to a faster scale-up of CCS and other emission-reducing technologies. The report looked at the challenges and opportunities in the VCM for ASEAN members. The absence of standard regulations and verification leads to slower growth in the VCM. Challenges such as lack of transparency around pricing and liquidity are hurdles to overcome to ensure integrity in the VCM (Rosales et al., 2021).

Although there is a lot of focus on all the barriers in the VCM, Miltenberger et al. conclude that the growing interest in the market and new investments in technologies will lead to barriers in the market disappearing (2021). The obstacles can be seen as growing pains for the growing market. When that is said, we do not escape the fact that the market must be developed in a direction that provides a higher standard. This will come automatically as the willingness to save the climate, and the environment becomes greater and more significant (Miltenberger et al., 2021).

Based on the literature review of the VCM, there are some hurdles to overcome for a well-functioning market. However, several studies believe that this can happen. Reviewing the literature, there is a lack of research reports about how the VCM is expected to be in 2030 regarding prices and traded quantity. Therefore, I will try to cover this gap by creating a state of knowledge market analysis of the VCM based on grey literature available from various sources and historical data.

## 2.2 Profitability of CCS at waste incineration plants

Torvanger (2021) calculated the cost of CCS at a waste incineration plant. The study is based on a case analysis of Fortum Varme at Klemetsrud. This is a plant that will capture 400 000 $tCO_2$ annually. The Levelized Cost of Carbon capture and storage is assumed to be 2 716 NOK/$tCO_2$ (Torvanger, 2021). This is a relatively high cost compared to a study conducted in Sweden (Johnsson et al., 2020). The Swedish study aimed to examine the cost of amine-based CCS in Swedish industrial plants with incinerators. These plants capture 500 000 t/$CO_2$ annually. The estimated Levelized Cost ranges between 80-135 EUR/$tCO_2$ (Johnsson et al., 2020). This is equivalent to 857-1447 NOK/$tCO_2$ using the NOK/EUR exchange rate at Norges Bank (Norges Bank, 2022). This is lower than the estimate of Torvanger. Increased inflation may have an effect, but this is minimal with a one-year difference in the analyses. Both estimates include the entire CCS value chain. Transportation and permanent storage are therefore included. Fuss et al. (2018) calculations indicate a Levelized Cost for CCS of combusting biogenic material with a range of 88-288 USD t/$CO_2$. This is equivalent to 715-2340 NOK/$tCO_2$. The significant price variation in estimated costs for CCS shows that this is a technology in development and that the costs vary greatly from project to project.

In another Swedish case study conducted by Fuss and Johnsson (2021), they investigated whether it is possible to implement CCS of biogenic emissions at the same rate as described in the IPCC report to reach the 1.5 target (Masson-Delmotte et al., 2018). They concluded that the current price level of $CO_2$ is too low for profitable investments in CCS. There is no technological barrier, but the incentives for CCS of biogenic emissions are absent and too weak. The CCS of biogenic emissions must be incentivized to a greater extent to achieve the goal described in the IPCC report (Fuss & Johnsson, 2021).

The importance of creating negative emissions will most likely increase the closer we get to the emission target and global warming over 1,5-2 degrees. Torvanger (2021) believes that the most significant barrier within CCS for waste incineration plants is that the costs are too high, at the same time as the price incentives for capturing biogenic emissions are too weak. He, therefore, proposes, among other things, that certificates for negative emissions must be introduced and governed by the Government. These certificates will have a value set by either the Government or the project developer for the negative emissions (Torvanger, 2021).

Pour et al. (2018) examined how CCS at waste incineration plants can contribute to creating negative emissions. Almost like Torvanger (2021), they suggested that a negative emissions refund scheme should be introduced. The waste incineration plant receives a refund for every ton of biogenic emissions captured. The market will not control the refund prices, the Government or the project developer will control a fixed refund price. They conclude that such a refund system will have a major impact on the profitability of CCS at waste incineration plants. Negative emissions and CCS of biogenic emissions could contribute to reaching the global warming targets if the policy is steered in the right direction (Pour et al., 2018).

Another approach that can contribute to incentives of investing in CCS is the possibility of saved costs. Midtun et al. (2019) carried out an analysis of the profitability of CCS at Klemetsrud and the extent to which profitability is affected by whether waste incineration plants are implemented in the EU ETS or not. The analysis results indicate that an increasing price of $CO_2$ and that waste incineration is included in the EU ETS can contribute to CCS profitability in such projects (Midtun et al., 2019).

Looking back at the literature review, it seems clear that investing in CCS at a waste incineration plant is not profitable without incentives. I will therefore try to examine whether the sale of voluntary carbon credits can be a good enough incentive to make CCS of biogenic emissions profitable for waste incineration plants.

# 3 Background

This chapter aims to create a context of the research questions and the basics needed for further understanding the thesis.

## 3.1 Carbon Capture and Storage at a waste incineration plant

CCS involve capturing $CO_2$ and preventing it from entering the atmosphere. As mentioned in chapter 1, there is a distinction between biogenic and fossil emissions. Waste incineration emits fossil $CO_2$ mainly when burning plastic and packaging, while biogenic $CO_2$ emission originates from burning biomass like food leftovers or other plant-based material. Biogenic emissions are considered climate-neutral because it only returns to the atmosphere, the carbon absorbed as the plants grow (IEA Bioenergy, 2022). Figure 1 illustrates the difference between biogenic and fossil $CO_2$ (Norsk Landbrukssamvirke, 2019).

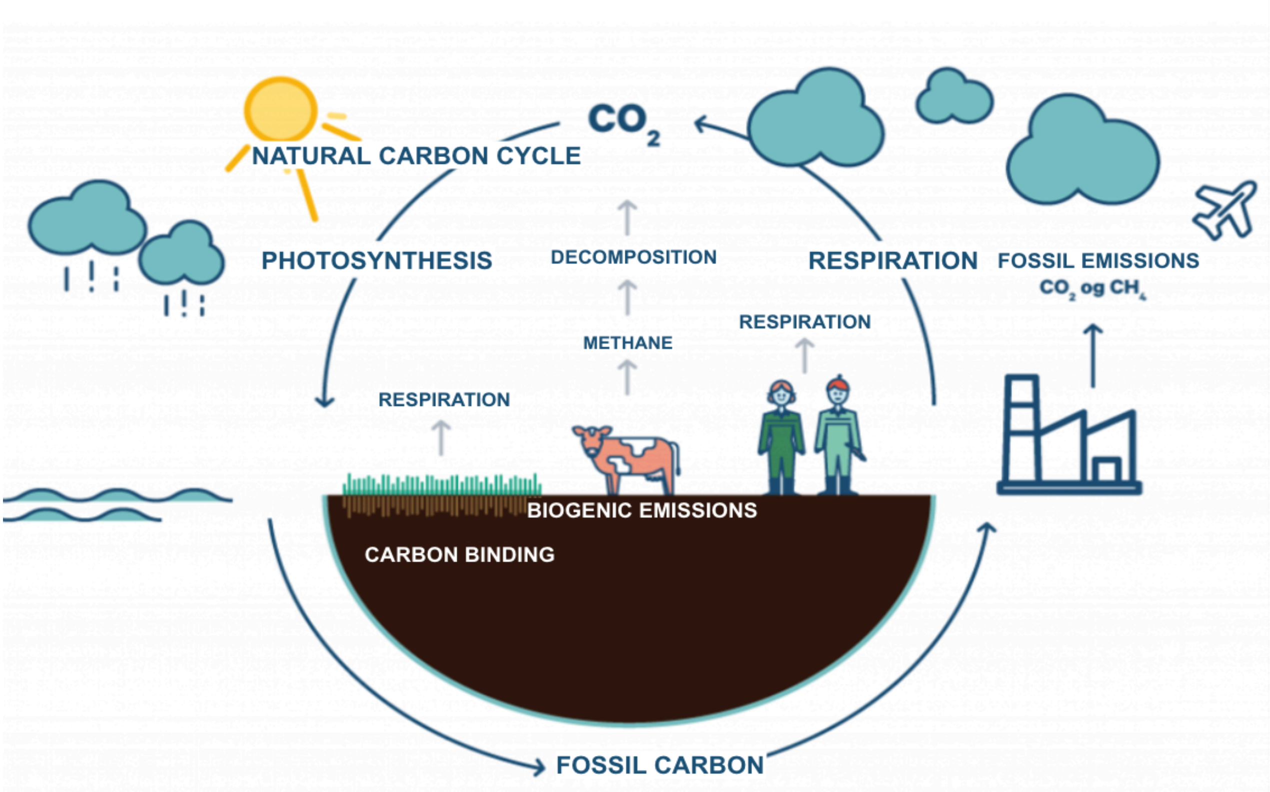


*Figure 1: The natural and the fossil carbon cycle. Illustration inspired by (Norsk Landbrukssamvirke, 2019)*

### 3.1.1 Description of the carbon capture process

The same technology is used at a waste incineration plant when capturing biogenic and fossil carbon. The process of carbon capture contains many different and complex operations. Figure 2 shows the passage of the capturing part for carbon capture. The process is briefly described stepwise in the section below (Aker Carbon Capture, 2021; Røsjorde, 2020).

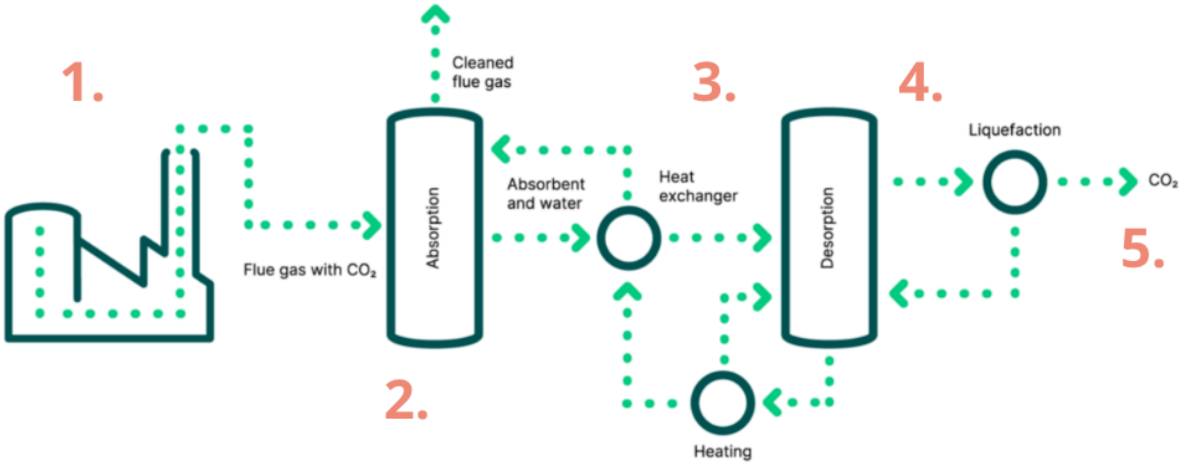


*Figure 2: The carbon capture process at a waste incineration plant (Aker Carbon Capture, 2022a)*

1. The flue gas is redirected from the chimney to the carbon capture plant. The flue gas is then cooled using water in the «absorption».
2. The «absorption» consists of two parts. There is an upward flow of $CO_2$ in the flue gas bound to a downward flow of amine solution in the lower part. The amine solution is a mixture of chemicals that bind the $CO_2$. In the upper part, the flue gas is washed with water so that amines are not released into the atmosphere before the flue gas is released into the air. This process removes about 90 percent of the $CO_2$ content from the flue gas.
3. The amine solution with $CO_2$ is then pumped from the «absorption» to the «desorption», where the amine is heated. The $CO_2$ from the amine solution is then released. The amin with a low concentration of $CO_2$ is pumped back to the «absorption» and reused.
4. $CO_2$ in gaseous form flows out of the top of the «desorption» and is exposed to pressure increase and additional reductions steps so that the $CO_2$ gas becomes liquid.
5. The liquid $CO_2$ is then pumped in pipes to the intermediate storage with specific pressure and temperature.

## 3.2 Externalities and Pigouvian taxes and subsidies

Two methods are mainly used in climate policy to achieve reduced emissions and climate benefits. These are subsidy solutions and tax schemes. The subsidy solutions should seem enticing, while the tax schemes work more like a whip.

Arthur Pigou developed the concept of externalities. Positive externalities are common benefits that you cannot take profit from, while negative externalities are common costs that one would not be charged directly for. This is a typical theory regarding emissions of greenhouse gasses and pollution. Pigou states that those who create positive externalities must be paid, while those who create negative externalities must pay (Pigou, 2002). Without any framework, the negative externalities will continue to happen, while the positive externalities will be absent (Caplan, n.a.). Such types of instruments are now called Pigouvian taxes and subsidies. In climate politics, we can see both of them (Amadeo & Anderson, 2022). EU ETS is a Pigou tax on negative externalities, while the VCM is a Pigou subsidy to positive externalities. The Norwegian Government uses a Pigou tax on waste incineration.

## 3.3 International climate commitments

Since 1992, several climate agreements have been made, which have formed a framework for national climate negotiations. The UN Convention on Climate Change in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015. The countries are bound, by those agreements, to meet annually for negotiations. These meetings are called the Conference of the Parties (COP) (Regjeringen, 2021a).

Even though the Paris Agreement came into force in 2016, there have long been some articles that have been missing regulations and standardization. This especially applies to Article 6 about purchasing and selling carbon credits. After COP26 in 2021, these regulations are finally in place (Regjeringen, 2021b). That the rulebook of Article 6 finally is in place has a lot to say about the credibility of the carbon markets, both the EU ETS and the VCM, and it’s future. How the voluntary carbon market is linked to the Paris Agreement and Article 6 is described in more detail in chapter 5.1.1.8.

## 3.4 Carbon prices

Today’s carbon market is mainly grouped into two main categories - the EU ETS, required by law, and the VCM, based on voluntariness. The EU ETS aims to reduce total emissions and capture fossil $CO_2$, while the VCM gives incentives to invest in projects that remove or create negative emissions (Schreiber, 2013). There are several different compliance markets in the world. The EU ETS is relevant for waste incineration plants in Norway. In addition to the EU ETS and the VCM, another critical tool for incentivizing emission reductions is $CO_2$ taxes.

### 3.4.1 Government-controlled carbon prices

The Kyoto Protocol set legally binding caps for the industrialized countries. Only the sectors subjected to quotas are affected by the agreement. Today, these are most emissions from oil and gas, industry and aviation (Miljødirektoratet, 2021b). National Framework on Climate

Change Norway became a part of the quota market through the EEA agreement in 2008 (Regjeringen, 2020). The EU ETS distinguishes between the quota-obliged and non-quota-obligatory sectors. The sectors defined as not subject to quota obligations are transport, agriculture, heating in buildings, waste, and the use of fluorinated gases. Therefore, these sectors are not regulated through the EU ETS (Regjeringen, 2020). This means the waste industry has no extra cost caused by the EU ETS in 2022. Even though waste incineration is not yet included in the EU ETS, an EU draft proposal has been published indicating that waste incineration will be implemented in the EU ETS by 1st January 2028. This means that the future EU ETS prices will most likely affect the profitability of CCS at a waste incineration plant post 2030 (European Commission, 2021b).

The EU ETS is based on a “cap and trade” system where the cap is the total amount of $CO_2$ that can be released each year (European Commission, 2021a). Furthermore, the system allows emission trading. Companies or countries with a surplus of allowance can sell these to those unable to cut their emissions sufficiently (European Commission, 2015). The cap is reduced with a linear reduction factor each year. This will ensure that the emissions are cut where it is most cost-effective to cut them. The cap will be adjusted and reduced over time so that companies have an incentive to invest in new and greener solutions (European Commission, 2021a). The goal is that the price of $CO_2$ will be so high that it will be profitable for firms to invest in energy efficiency measures, or CCS, rather than continue to pay the allowance price. Each company will cut emissions until the cost of taking measures is higher than buying a carbon quota in the market. The market is thus governed by two mechanisms: cap and demand in the market. The authorities determine the cap for emissions, but the price is determined based on what the market is willing to pay (Lovcha et al., 2022).

Another critical tool to reduce emissions is $CO_2$ taxes. The authorities set a price on emissions. Waste incineration is subject to a separate rate on the fossil emissions in Norway (Skatteetaten, 2021). This is the opposite of how the EU ETS works. The authorities set the price, and the market determines how large the emissions cut will be (C2ES, n.a.).

### 3.4.2 The Voluntary Carbon Market

The VCM, also called the carbon offset market, is relative to the EU ETS and the $CO_2$ tax, based on voluntariness and companies’ desire to reduce emissions. The VCM allows $CO_2$ emitters to cut difficult or impossible emissions (Favasuli & Sebastiian, 2021). A voluntary carbon credit cannot replace fossil emissions and does not increase the number of allowances in the EU ETS (Climate Corporation, n.a.).

Buying carbon credits in the VCM is currently used mainly by companies to show social responsibility and establish a green image and reputation (Climate Corporation, n.a.). Another thing that separates the two carbon markets is that in the VCM, there are no clear regulations. The calculation and the certification are implemented by several industry-created standards (Climate Corporation, n.a.). The VCM will be described in more detail in chapter 5.1.1.4.

In addition to VCM, there is a Clean Development Mechanisms (CDM), which also originates from the Kyoto Protocol. Emission-reduction projects could be used to cut emissions toward the goals of the Kyoto Protocol. Surplus from these emissions cuts is sold on the VCM today. It is important to be aware of this, but these will not be analyzed separately from the VCM in this thesis (Cornillie et al., 2021; UNFCCC, n.a.).

# 4 Theory and method

In this chapter, the theory and methods used to analyze the voluntary carbon market and the profitability of CCS at a waste incineration plant will be presented. This chapter will be divided into two parts. The first part presents the theory and methods used to answer sub-question 1: how to analyze the Voluntary Carbon Market and the expected prices and quantity of carbon credits towards and after 2030. This sections also explain how the expectations for the prices of carbon quotas in the EU ETS are analyzed. The second part presents the theory and methods used to answer sub-question 2: how to analyze the profitability at a waste incineration plant.

## 4.1 Market analysis

The main point of the market analysis is to find good enough results that can be used to answer sub-question 2. To gain a comprehensive understanding of the market, there is important to analyze the entire market and not just what is relevant for CCS at a waste incineration plant. The market design will be analyzed and described. Whether there is a difference between different carbon credits and what drives the prices will be examined. The market analysis is based on both descriptive statistics and literature research. Using descriptive statistics to find trends and connections in the data (Lee et al., 2013).

To examine whether there are any clear trends in the market, a descriptive statistical analysis of historical prices and demand is carried out for the two markets. Drivers in the market were then mapped based on gray literature and report findings. It is examined how the mapped drivers can affect the future of the VCM. Finally, a literature search was conducted searching for price expectations in the VCM. The price scenarios are estimated using insight achieved in the market analysis and combine the quantitative and the qualitative results.

The market analysis is divided into two parts where the first part being about the EU ETS and the second part about the VCM. The EU ETS analysis is a small part of the market analysis and is only carried out to understand better the VCM and how the two markets may be connected in the future.

### 4.1.1 Data

Information about the market is mainly found by literature research. The literature research involves finding relevant literature about how the markets are expected to develop in the years ahead and after 2030. This implies expected demand, supply, prices, and other essential aspects affecting the VCM.

The VCM is not a well-documented field of study, and the market is unknown to many. This makes it challenging to find good literature. Insight into the market is conducted mainly by grey literature like reports from companies, organizations, research groups, EU documents, and documents of the Norwegian Government. The main reports used in this thesis have been reviewed and written by TSVCM, Trove Research, Bloomberg, and McKinsey. Reports from large companies such as Shell and Microsoft have also been used. The existing literature is often carried out by people interested in a well-functioning VCM, this can therefore color the articles.

Ecosystem Marketplace's latest report contains reporting from 172 project developers, investors, and intermediaries worldwide in the VCM. The report is assumed to give a correct picture of historical prices and volumes in the VCM (Donofrio et al., 2021). To find the average historical price and volume traded in the market, data is retrieved from the database of Ecosystem Marketplace. The data contains average annual prices distributed on continents. The yearly price is calculated by finding the average price of the different continents. This can give a wrong impression as the prices in the market vary wildly based on the different price drivers. I would have needed more detailed data to find the exact expected prices the waste incineration plant can achieve from selling carbon credits.

In addition to the Ecosystem Marketplace, historical data is taken from Trove Research. A challenge associated with retrieving historical data is that it often varies from source to source. Both the Ecosystem Marketplace and Trove Research are based on companies voluntarily reporting purchases and sales of carbon credits. It is not a joint body that collects all the credits sold in the market. Companies are voluntary to report both the price and the volume traded. This voluntariness means that the data from the two sources vary. This has also made it challenging to obtain newly updated data, and the latest updates are, therefore, from August 2021.

Data is also collected from the Berkeley database containing voluntary registry offsets. This database includes information about historical transfers from the four major verification organizations that generate almost all the credits on the VCM. This database is created to create more integrity in the market.

The data containing prices from the recent months is taken from CarbonCredits.Com, a collection page with the latest news on carbon prices. The historical prices in the graph of CarbonCredits.Com are taken from Verra, one of the market's largest verification organizations. As this data only contains data from Verra and no other verification standards, the source is considered to be somewhat poorer in quality. It is nevertheless expected to indicate trends in the market.

Another important point that can cause the volume and price to vary in the various data sources is that the purchases and retirement of the credits do not have to be in the same year. This means that it is possible to buy a credit that occurred in a previous year, or you can buy a credit where the capture will happen in the future. This causes problems regarding which year the credit is registered. The most essential point with the historical data, however, is to see if there are any trends or connections, and this is considered possible with the collected data.

## 4.2 Investment analysis

This subchapter presents the theoretical foundation for the investment analysis in chapter 5.2. I apply the net present value rule for assessing the profitability of the investment projects and look at the incremental cash flow of the project. This means that I look at the differential cash flow of a waste incineration plant with CCS and a plant without CCS.

#### 4.2.1.1 Net present value

The net present value (NPV) approach assesses whether selling biogenic carbon credits can ensure profitability in CCS investing. The goal of calculating the NPV is to measure the creation of value of the investment (Chiesa & Frattini, 2009). The NPV involves discounting all future cash flows for the project with a discount rate and then summing them together (Khan

& Jain, 1999). An investor should invest if the NPV shown in Equation 1 is positive (Bøhren & Gjærum, 2020).

Equation 1: Net Present Value (NPV)

$$NPV = -I + \sum_{t=0}^{t} \frac{ICF_t}{(1+r)^t} > 0$$

*$ICF_t$: incremental cash flow*

*t: year*

*r: discount rate*

*I: investment in year 0*

The Internal Rate of Return (IRR) is used to complement the NPV method. The IRR measures the percentage return on the capital tied to the project at all times. When using the IRR method, a positive rate is no longer sufficient for the project to be defined as profitable. Projects, where the IRR is lower than the discount rate should not be invested in (Bøhren & Gjærum, 2020).

### 1.1.1 Cash flow budgeting

Waste incineration and emissions are associated with $CO_2$ pricing and climate politics. For instance, income from selling carbon credit on the VCM and avoided costs from $CO_2$ taxes and carbon quotas in the EU ETS. To obtain a comprehensive assessment of these incremental cash flows, the entire value chain of CCS is included, from capture and transport to storage in the North Sea. This is partly because it must be documented that the $CO_2$ is stored to sell a carbon credit.

The cash flow describes the project's annual financial consequences. I focus on the cash flow to the total capital before tax; thus, neither funding nor taxes are included. All prices and the discount rate are given in real terms (2022 kroner).

#### 4.2.1.2 Levelized cost of carbon capture and storage

The cost associated with investing and operating CCS at a waste incineration plant is stated as a Levelized Cost of Carbon Capture and Storage (LCOC). To find the cost of the investment in year 0 and the annual operation and maintenance cost, the formula for LCOC is used. The LCOC is given by the Equation 2 (Ashkanani et al., 2020).

Equation 2: Levelized Cost of Carbon Capture and Storage (LCOC)

$$LCOC = \frac{(f_{CR} + f_{O\&M}) \sum(capital\ cost)}{f_c * (tons\ of\ \frac{CO_2}{year})} + \frac{\sum(operatin\ cost)}{(tons\ of\ \frac{CO_2}{year})}$$

*$f_{CR}$: capital recovery factor*

*$f_{O\&M}$: operating and maintenance cost factor*

*$f_C$: capacity factor*

In the absence of information on the $f_{CR}$, $f_{O\&M}$, and $f_c$, these are set equal to one. The distribution between the capital and operation cost was mapped by literature search and are explained more clearly in chapter 5.2.1.3. I find the capital and operation and, maintenance costs by using the equation. The cost of capital is the investment's net present value converted to an annual cost. The capital cost calculation is shown in Equation 3 (Brent, 2006).

*Equation 3: Capital Cost*

$$Capital\ cost = I * A$$

*I: investment cost in year 0*

*A: annuity factor*

#### 4.2.1.3 Discount rate

The discount rate should reflect the cost of risk of investing in the project. This should include: time cost - money is more valuable today than tomorrow, inflation cost – the purchasing power of money decreases, and risk cost – secure money is worth more than unsecure money. The main principle is to charge the investment project for risk at a risk-adjusted rate. The Capital Asset Pricing Model (CAPM) describes how the discount rate must be equal to the risk-free interest rate and a surcharge adjusted for risk (Bøhren & Gjærum, 2020). This is shown in Equation 4.

*Equation 4: The Capital Asset Pricing Model (CAPM)*

$$r = r_f + \beta * [E(r_m) - r_f]$$

$r_f$: risk-free rate

$E(r_m)$: expected return

$\beta$: the beta value of the project

The estimated beta value varies from investment project to investment project and should reflect the systematic risk. Systematic risk is risk associated with factors that are sensitive to economic conditions in the market. The systematic risk must be assessed against how sensitive projects are too high and low economic conditions in the market (Hagen, 2011). Since the cash flow is set up in real terms, the discount rate must be real and deducted from inflation (Shannon & Roger, 2008).

The discount rate in the base scenario of the analysis will be risk-adjusted. The risk will be illustrated in the remaining scenarios by carrying out sensitivity analyses, and the discount rate will be lower (Bøhren & Gjærum, 2020). The risk-free discount rate should only reflect expected alternative income on a risk-free basis for the investor (Shannon & Roger, 2008).

### 4.2.2 Sensitivity analysis

To map and minimize risk, a sensitivity analysis was performed to check the most uncertain factors and how they can affect the project's profitability (Bøhren & Gjærum, 2020).

#### 4.2.2.1 Star chart

A star chart illustrates how the project's NPV at a risk-free interest rate changes if the budget's basic assumption does not happen. The star chart shows how the project's NPV changes based on a percentage change in one by one variable. The star chart compares the different NPV profiles against each other, and it is clear which variables have the most significant effect on profitability. The impact of each risk source is displayed. This indicates how solid the project is for change at the same time as the most significant uncertainties are mapped (Bøhren & Gjærum, 2020).

#### 4.2.2.2 Scenario analysis

Scenario analysis is also carried out. This is a slightly more advanced type of sensitivity analysis. This method considers that two or more factors influence each other (Bøhren & Gjærum, 2020). The expected relationships between variables are then analyzed and mapped. The different outcomes turn into different scenarios (Hassani, 2016). This is more likely in reality, but it can be challenging to know which factors affect each other and how they affect each other (Bøhren & Gjærum, 2020). Therefore, the different scenarios will be discussed and are based on findings in the market analysis.

### 4.2.3 Data

Information has been obtained from various data to identify the cost picture at such a plant. The data basis for the profitability analysis is partly based on the results from the market analysis, at the same time as data directly associated with CCS at waste incineration plants have been obtained. Data obtained from the market analysis are expected prices in the VCM that will lead to income and expected prices in the EU ETS leading to saved costs.

Due to the confidentiality and increasing competition around CCS, it is difficult to find accurate and detailed cost estimates for investments and annual costs. The estimates of LCOC are taken from a project by Lyse, Bellona, CICERO, Aker Carbon Capture, and Forums Energigjenvinning that has yet not been published (Aspelund et al., 2022). The waste incineration plant and the data used in the profitability assessment are only to exemplify how typical costs are expected to be for such facilities and are not taken from an existing facility. The LCOC is based on different cost estimates collected from various suppliers and gives only an overall picture of the expected costs.

# 5 Results

This chapter presents the results found in the thesis. First, the findings from the market analysis of the VCM are presented and then the findings from the profitability assessment of CCS at waste incineration plants are presented.

## 5.1 Market analysis of the VCM

The purpose of this chapter is to analyze the first sub-question announced in chapter 1.2:

1. *How will the voluntary carbon market and the prices and quantities of the carbon credits traded there develop towards and after 2030?*

The development of the VCM is uncertain. Expectations vary among market participants concerning the future size of the market and the prices of the credits (Hong, 2022). As mentioned in the background, there are mainly two carbon markets. The focus of this chapter is to analyze the market prospects for the VCM, but there will also be a superficial view of the prospects of the EU ETS as this may affect the VCM. The goal is to identify different price scenarios in the two markets towards and after 2030.

### 5.1.1 The EU ETS

This chapter begins with an analysis of the historical prices in the EU ETS. Then comes literature research with different market expectations towards and after 2030. Based on these analyzes, different price scenarios have been set up for the expected price in the EU ETS towards and after 2030.

#### 5.1.1.1 Historical prices

Historically, the cap-and-trade system of the EU ETS has not always worked as it should. As an aftermath of the financial crisis in 2008, the supply was much higher than the demand. As a result, prices for carbon quotas were very low. It was cheaper to buy carbon quotas than to invest in emission reduction measures (Lovcha et al., 2022).

To establish control over the market again, the EU implemented The Market Stability Reserve (MSR) in 2019 (Eriksrud, 2022). The main principle of the MSR is that quotas not used during a year are retained and placed in a reserve for market stability. This means that they cannot be auctioned the following year, and the surplus of carbon quotas is removed from the market. MSR led to faster market regulation and created a more robust EU ETS market (Regjeringen, 2018). After introducing this regulation in 2019, the market is again governed by supply and demand. There has been an evident rise in the price in recent years. Figure 3 shows the dip in the market in the years after the financial crisis, how the measures introduced in 2019 reduced supply and how the prices went up.

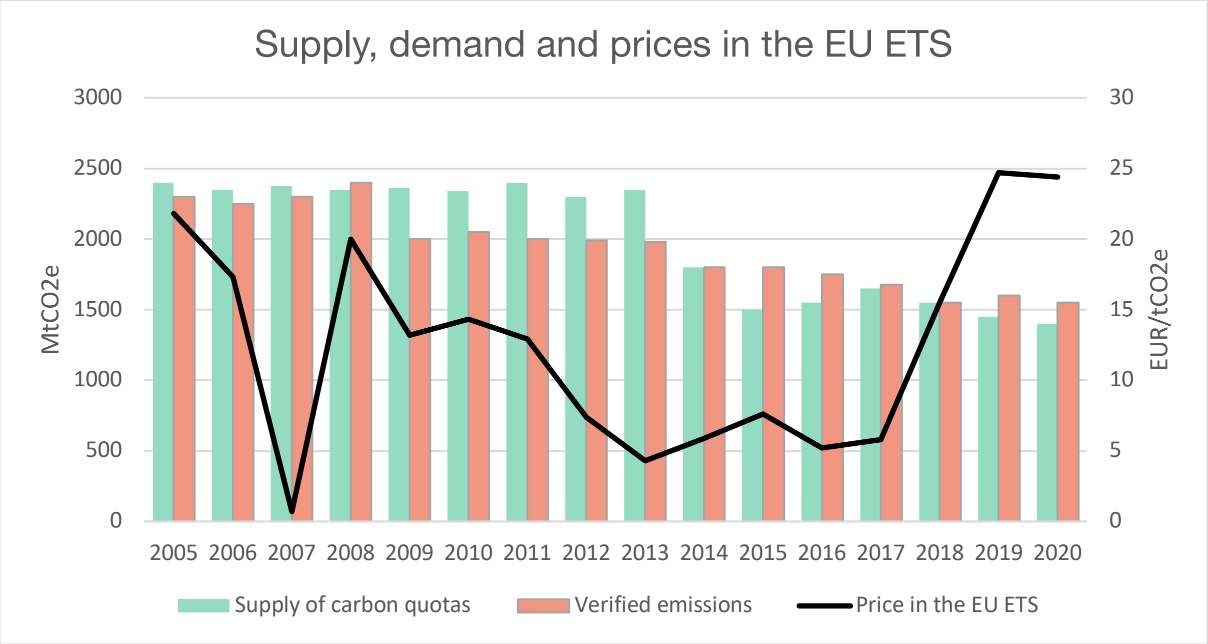


*Figure 3: Supply, demand and prices in the EU ETS* (European Environment Agency, 2022)

The period from 2020 to 2022 also shows a positive trend. The market mechanism has worked better, and prices have increased steadily over the past year. Figure 4 shows the prices of quotas in the EU ETS the previous year. This indicates that the prices of the carbon quotas have been relatively stable and high. It shows prices around 80 EUR/tCO2 in 2022. As the future cap declines, prices are expected to rise further (Carbon Credits, 2022). There is a slight dip in the market in the transition between February and March 2022 due to Russia´s invasion of Ukraine. It is uncertain how this will affect the market in the future (Quantum Commodity Intelligence, 2022).

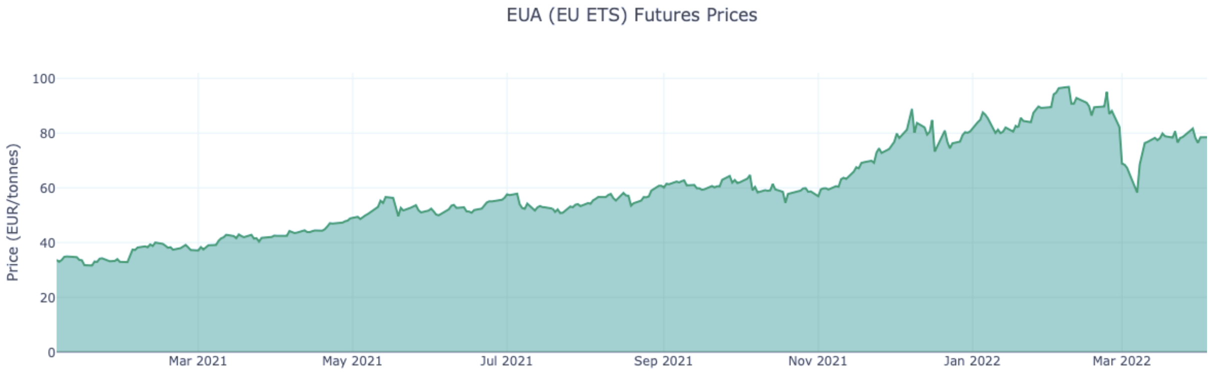


*Figure 4: EU ETS prices the previous year (Ember Climate, 2022)*

The dip in the market shows how gas and uncontrollable events can affect the price and make the market more volatile. The Russian invasion of Ukraine is an example of how gas prices affect the prices in the EU ETS. Russia is a major supplier of gas to Europe, and this, therefore, affected the price to a large extent. However, a market collapse similar to the one we saw after the financial crisis is not likely due to the new MRS regulation (Nicholls, 2022).

#### 5.1.1.2 Expected EU ETS prices in 2030

The EU has determined that the new net emission reductions should be at least 55 percent by 2030 compared to 1990 levels. The previous target was 40 percent. The EU ETS is considered crucial to achieving the overall target and must be at the same level. Therefore, the EU presented a legislative proposal to revise the EU according to the EU's Fit for 55. To reach this target, the new proposal is an annual reduction factor of 4,2 percent, instead of 2,2 percent (European Commission, 2021b; European Commission, 2021c).

In a report by Pietzcker et al. (2021), they predict that the EU ETS price will increase to 129 EUR/t$CO_2$ in 2030. This analysis is based on the new targets of the EU and compares it with what the expected prices would have been with the old scenario. The model has included the following four dimensions: the new emission target, electricity demand, the investments in transmission capacity, and the availability of CCS and nuclear technologies (Pietzcker et al., 2021).

Florian Rothenberg (2021), an analyst on EU power and carbon markets in ICIS, says in an interview that based on analysis by ICIS, they believe that the EU ETS prices will hit 90EUR/t$CO_2$ by 2030. The estimate is based on the expectation of a tight EU ETS market towards 2030, caused by a combination of the higher cap reduction and the MSR. He also points out that the low supply of gas and the following uncertainty are important factors for the high price (Simon, 2021).

According to CRU Group's analysis and their carbon abatement curve for 2030, the EU ETS price will reach 140 EUR/t$CO_2$ by 2030. The carbon abatement curve illustrates the $CO_2$ prices that give an incentive to invest in new technologies rather than paying carbon quotas (Butterworth, 2021). Carbon Pulse is skeptical of the high EU ETS price estimate from the CRU Group and refers to their own latest article, where they have interviewed ten analysts who are experts in the field. The average estimated price in 2030 reaches 97 EUR/t$CO_2$ and is partly lower than the analysis by CRU Group. The argument is based on the new emission target, political pressure, MSR, and gas prices (Carbon Pulse, 2021).

Modeling carried out by Network for Greening the Financial System (NGFS) shows that to achieve the goal of net-zero in 2050, the price must be around 180 USD t/$CO_2$ in 2030 (NGFS, 2021). It is important to note that this is the average price based on international commercial quota markets and is not specified to apply to the EU ETS. Nevertheless, it is natural to expect that international prices will be relatively similar. It is also important to note that these prices are in 2010 prices and will have a higher value in NOK 2022.

To make the estimates from the different analysts comparable and usable in later calculations, all estimates have been converted to NOK and 2022 prices. Figure 5 summarizes and illustrates the various estimates.

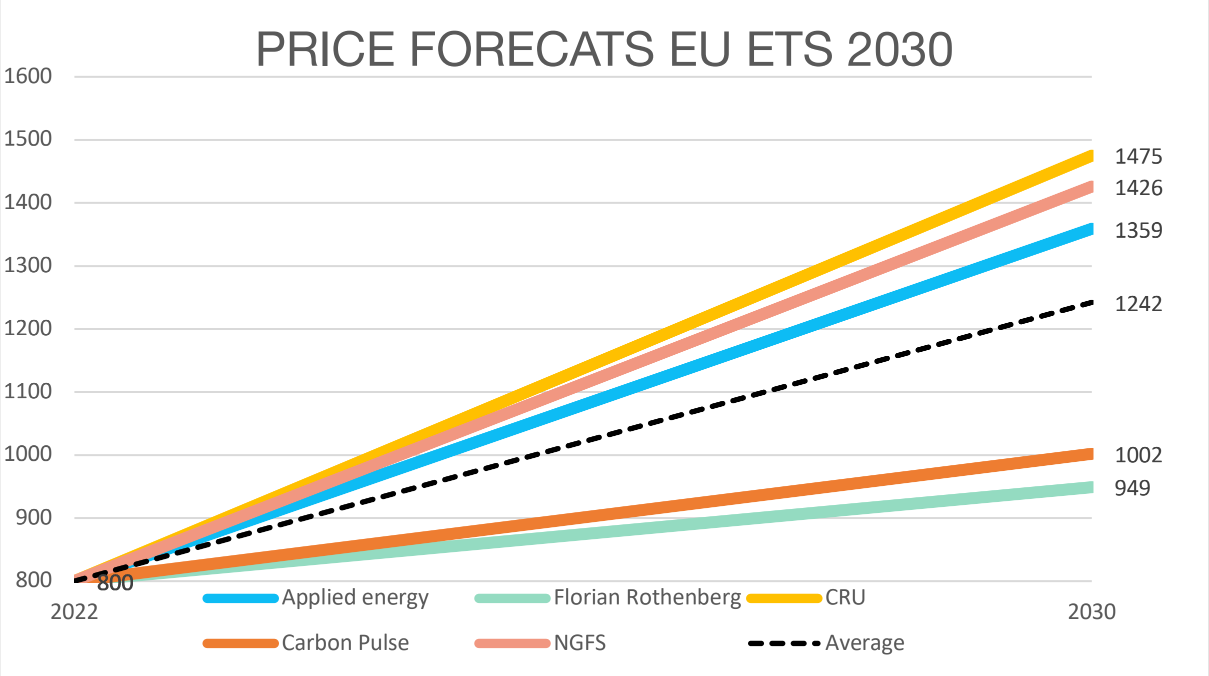


*Figure 5: Summarize of various price forecast in the EU ETS by 2030*

#### 5.1.1.3 Price scenarios in 2030

As it appears in chapter 5.1.1.2, there is a considerable variation in the expected price in the EU ETS towards and after 2030 based on different analysts. It turns out that the same arguments are used in a wide variation in prices. Expected prices are therefore based on descriptive statistics. The three scenarios are presented in Table 2.

*Table 2: Price scenarios in the EU ETS*

| PRICE SCENARIO | EU ETS PRICE IN 2030 |
|---|---|
| LOW | 949 NOK/tCO2 |
| BASE | 1242 NOK/tCO2 |
| HIGH | 1475 NOK/tCO2 |

The base scenario is an average of all estimates found. The high and low estimates are based on the highest and lowest estimates found in the market analysis. Including both the highest and lowest estimated value makes it possible to include the entire uncertainty interval. Regardless of the price estimate, the price is expected to increase by 4,2 percent.

### 1.1.1 The Voluntary Carbon Market

The prices in the VCM vary much more and have a larger price range than EU ETS (puro.earth, n.a.). The VCM is quite different, and the market's structure, pricing, and challenges are examined in the following subchapters before historical aspects are analyzed. Then comes literature research with different expectations of the market. Based on these analyzes, different price scenarios have been set up for the expected price in the VCM towards and after 2030.

#### 5.1.1.4 The Structure of the VCM market

To understand the VCM, the structure of the market is analyzed. Figure 6 illustrates how the VCM works and what phases the credits go through (Favasuli & Sebastiian, 2021). The figure and the definitions are described in the section below.

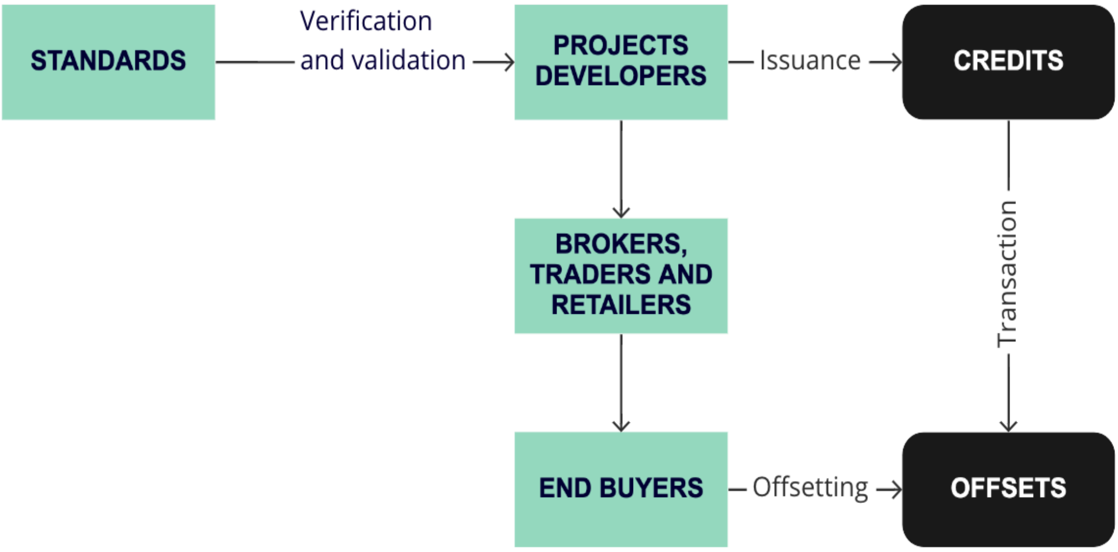


*Figure 6: Structure of the VCM. Illustration inspired by* (Favasuli & Sebastiian, 2021)

**Project developers** invest in a carbon capture project and sell voluntary carbon credits. They can be individuals, organizations, or businesses with projects that create credits (Favasuli & Sebastiian, 2021). A waste incineration plant with CCS is an example of this. Project developers include everyone involved in the process, from the project design to the issuance of the credit (Ecosystem Marketplace, u.a.).

Some project developers sell credits directly to the end buyers. Others sell them through a broker, an exchange, or a retailer who resells the credits (Chen et al., 2021). The process may vary since there is no centralized voluntary marketplace.

**Retail traders** collect big amounts of carbon credits directly from the project developers. They then create portfolios with various credits containing different sizes and the number of tons of $CO_2$ caught. These portfolios are sold to the end buyer, and the retailers profit from the composition and sale (Favasuli & Sebastiian, 2021).

Most purchases are made privately and are over-the-counter agreements, but some exchanges have appeared in recent years (Chen et al., 2021). Although the stock exchanges have tried to simplify the trading process with standard products to ensure basic principles, this is challenging as the pricing of the credits is complex and challenging (Favasuli & Sebastiian, 2021).

**Brokers** buy the carbon credits from the retail traders and communicate the portfolios to the end buyers with some commission (Favasuli & Sebastiian, 2021). They act as an intermediary that facilitates trade between sellers and buyers (Ecosystem Marketplace, u.a.).

**End buyers or final buyer** buy the credits and aim to cut emissions (Chen et al., 2021). They can be large companies, private individuals, or small organizations. Large companies such as Apple, Microsoft, Shell, and Google are buying credits on the VCM (Favasuli & Sebastiian, 2021). Once an end buyer has purchased a credit, the carbon credit will "retire". This means that the credit can no longer be resold after it has been used to cut emissions by the end buyers (Cornillie et al., 2021).

**Standards** include quality criteria that must be met before any emissions reductions can be certified as carbon offsets (Stockholm Environment Institue & Greenhouse Gas Management Institute, n.a.-a). Standards Organizations are usually voluntary organizations that certify the projects. This includes checking and verifying whether the projects achieve the stated emission volumes (Chen et al., 2021). There are different methods and requirements for the different projects. For example, there are separate rules for calculating the uptake from forests than from CCS at a waste incineration plant. This determines the number of carbon credits produced over time (Favasuli & Sebastiian, 2021). Most projects and programs have a library of approved methods and criteria covering many project types (Stockholm Environment Institue & Greenhouse Gas Management Institute, n.a.-a).

The standard certifications shall also ensure that specific requirements for CCS are respected and complied with. Those core principles include additionality, overestimation, duration of storage, exclusive claim, and avoiding double-counting, providing additional social and environmental benefits (Favasuli & Sebastiian, 2021). The core principles help determine the prices of carbon credits and are described more in detail in chapter 5.1.1.5. However, project accounting of the resulting carbon removal is often unclear and complicated (Microsoft, 2021). The challenges of the VCM will be communicated and described deeper in chapter 5.1.1.6.

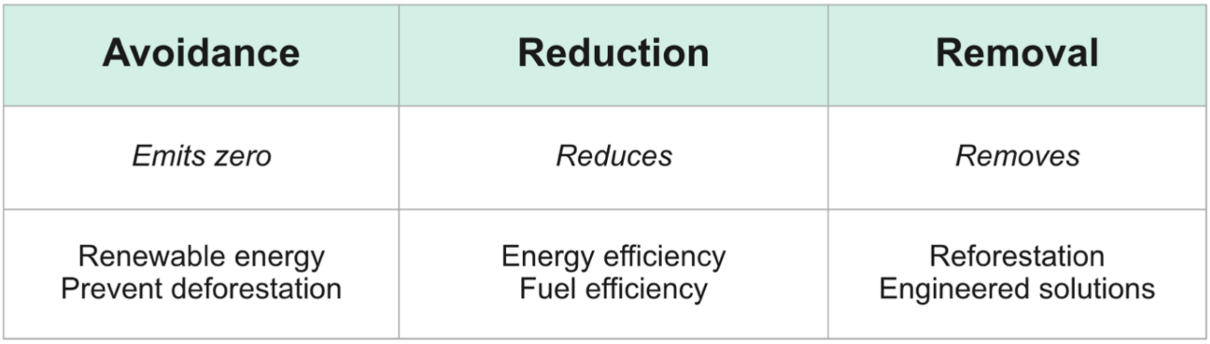
#### 5.1.1.5 Pricing in the VCM

For a carbon credit to be sold on the VCM, the only requirement is that the ton of $CO_2$ captured or removed from the atmosphere is not a part of a compliance market. Both supply and demand vary greatly based on the type of project (Favasuli & Sebastiian, 2021). According to literature research described further in this chapter, there are mainly six factors that affect the price. These factors are listed in the following chapter and are seen in connection with how this affects the prices of credits from waste incineration plants.

**The methodology** says something about the type of projects and the origin of the carbon credit. The market distinguishes between different qualities of carbon credits. High quality leads to a higher price (Shell & BCG, 2021). However, it is not entirely straightforward to decide whether a credit is of high quality or not. All methods are priced differently, and the credit quality is based on several factors.

Carbon credits fall into one out of three categories depending on: avoidance, reduction, or removal. Avoidance projects include projects that emit zero $CO_2$, such as wind, solar, hydropower and biofuel projects. The reduction contains projects that reduce $CO_2$ emitted compared to the baseline or the company's business-as-usual. This can be by reduced energy demand, fuel efficiency, or other energy-saving measures. Removal is projects that remove $CO_2$ from the atmosphere and store it through reforestation or engineered solutions that catch $CO_2$ (Mazzochi et al., 2021). Table 3 shows the tree categories. It is important to note that prices vary widely within and across these categories. The waste incineration plant will be priced as an engineered removal project.

*Table 3: Main categories in the VCM*



| **Avoidance** | **Reduction** | **Removal** |
|---|---|---|
| *Emits zero* | *Reduces* | *Removes* |
| Renewable energy<br>Prevent deforestation | Energy efficiency<br>Fuel efficiency | Reforestation<br>Engineered solutions |

**Additionality** says something about what would have happened if measures had not been implemented (Regjeringen, 2011). Emission reduction, avoidance, or removal is defined as additional if it had not occurred without the carbon credit (Broekhoff et al., 2019). If those who sell the carbon credit can guarantee that the uptake of $CO_2$ would not have happened without the income, the credit can in theory be valued as high as the Levelized Cost of CCS. The challenges related to additionality are described in more detail in subchapter 5.1.1.6.

The advantage of CCS at a waste incineration plant is that such a project will have a precise cost that revenues from carbon credits must cover. It is easy for a waste incineration plant to document the actual cost associated with the capture and storage. Using the calculations, it is easy to document the income from the credits for the project to be considered profitable. It is considered additional if the credits contribute to the CCS at waste incineration becoming profitable. In theory, this means that the expected prices of credits sold from CCS at waste incineration should be high enough to cover the costs.

**Co-benefits:** an example of co-benefits is when planting new forests for carbon capture results in an improved ecosystem for species or restoration of damaged habitats. If a carbon project leads to co-benefits, the carbon credit will be valued higher (Microsoft, 2021; Shell & BCG, 2021). In particular, co-benefits that support the UN's climate goal, such as educational, environmental, economic, and social co-benefits, help drive prices up. An example of such benefits can be when an engineered project is established in a developing country. This can lead to co-benefits such as local education and job-creating in the community. Such projects require manpower and educational training in the newly introduced technology. Preventing deforestation can lead to co-benefits like improved biodiversity. By preventing deforestation, pollution of drinking water sources is avoided, and species in the area are saved (Woodside & Affendy, 2020). There are co-benefits for both engineered solutions and nature-based solutions. Since co-benefits are a criterion that is highly valued in the market, the willingness of companies to pay will lead to credits arising from such a project (Microsoft, 2021). Co-benefits apply mainly for projects in developing countries. This is often problematic, as the projects that claim to have co-benefits often have poor documentation. The countries' lack of digitization and systems makes verification even more challenging (PwC & Zero, 2022).

CCS at a waste incineration plant in Norway will mainly not lead to any co-benefits other than removing $CO_2$ from the atmosphere. It can be argued that such a project is important considering the green shift and creation of new jobs, but since Norway is considered a developed country, it is exaggerated to argue that this affecting the price of the credit. Therefore, it is unlikely that co-benefits will contribute to driving up the credit prices sold by the waste incineration plant.

**Duration and risk of a premature release:** Duration indicates how long the captured $CO_2$ will be captured and for how long the actual capturing of new $CO_2$ takes place. Premature release means that the captured $CO_2$ is released earlier than the stated duration (Broekhoff et al., 2019). There is always a risk that trapped carbon will be re-released into the atmosphere. A carbon credit can be priced higher if the project developer can guarantee that the carbon remains captured and stored for a given period. Insufficient guarantees will drive down the price of the credit. This is difficult to document as different methods and verification methods are used in the market (Shell & BCG, 2021).

The risk of premature release is exceptionally high with natural solutions, and the duration of the storage is shorter. A planted forest will absorb and store $CO_2$ throughout its life cycle, but the trees will eventually die and release the captured $CO_2$ again. Another aspect is that it is difficult to document whether the tree absorbs the same amount of $CO_2$ throughout the life cycle period. Projects such as afforestation and plant foresting make it challenging to guarantee that the carbon stays captured in the duration period because of the risk of unforeseen forest fires or other natural disasters. Since both the time horizon for the carbon captured and the risk of release will affect the willingness to pay, there is a significant difference in expected price between natural and engineered based solutions (Favasuli & Sebastiian, 2021; Microsoft, 2021).

CCS at a waste incineration plant is an engineered solution that indicates that the capture has an eternal duration and the risk of premature release is very low. This will drive up the carbon credit price originating from the waste incineration plant.

**Documentation and verification standards** can vary since there is no standard standardization for the VCM. The perception and the validity of the credit verification affect the price. If the certification seems well developed and documented, this will help to drive the price up (Shell & BCG, 2021). There are some recognized standards for documentation and verification. If a recognized institution has approved the project, the price can be set higher than if it is a new and unknown standard. The dominant ones in today's VCM are Verra (VCS) and Gold Standard (PwC & Zero, 2022). The methods for calculation and documenting for the various projects are open and accessible to everyone through Verra and Gold Standard (Gold standard, n.a.-b; Verra, 2022). This makes it easy for the end-buyers to know what they are paying for. The credit quality increases because it is well documented how it is priced and how the capture is estimated.

For example, it is difficult to quantify how much $CO_2$ a specific tree absorbs during its lifetime. That there is no standard method for such calculations makes it challenging. This also applies to CCS at a waste incineration plant. Considering that waste incineration plants can have seasonal variability of carbon intake, the accounting for and verifying of how much emission is biogenic, or fossil is tricky. The waste mix changes from period to period, and the distribution will change over time (ROAF, 2020). Another important question is who decides this distribution. Is it the different verification standards in the VCM, or must the Government determine it?

**The vintage of the credit** describes the year the emissions reduction or removal occurred. Since the supply of carbon credits has been higher than demand, there are currently many old credits on the market at a very cheap price (PwC & Zero, 2022). This is partly due to the old credits from the CDM market (Ecosystem Marketplace, 2021b). The longer it is since the emission reduction or the removal happened, the cheaper the price will be. The challenges associated with historical credits still being on the market are described in more detail in subchapter 5.1.1.6.

It is difficult to determine how this price driver will affect the carbon price expected for the waste incineration plant. The main goal of the plant is to sell the credits before or at the same time as the capture occurs; this will drive up the prices. In the event of low demand in the market, this will nevertheless cause the plant not to be able to sell all the credits in the current year. If they then sell these credits in the coming year, this could lead to reduced prices.

#### *5.1.1.6 Challenges in the VCM*

Even though the VCM started to develop in 2005, the market is nascent and undeveloped (Microsoft, 2021; Stockholm Environment Institue & Greenhouse Gas Management Institute, n.a.-b). To achieve a credible and stable VCM, it needs to overcome some hurdles. This chapter will highlight the biggest challenges in the VCM as of 2022.

**A lack of transparency** makes it challenging to set prices correctly in the market. There is a lot of secrecy among companies regarding the purchase and sale of credits. As described in chapter 5.1.1.5 there is a variation in the prices based on different market aspects and the carbon credit. This makes it difficult for both the end-buyers and the sellers to assess whether they are paying or charging a reasonable price for the project. This makes it especially challenging for the project owner to handle and assess the risk associated with expected income (PwC & Zero, 2022).

**Double-counting** is a significant problem and is one of the main ways that integrity is undermined in the market (Schneider et al., 2019). The problem is that the offsets from a carbon credit can be used two times or more. A carbon project in one country can reduce the country's emissions regarding the targets in the Paris Agreement, and then carbon credits from the same project can be sold to a company in another country on the VCM. Then both the government and the business claim to have reduced emissions which only happened once (Gold standard, 2021; Honegger et al., 2021).

The goal of the credit being retired when companies or individuals claim the offset is to avoid double-counting. Each carbon credit has its unique number to control this. The problem is that there is no common database for these unique numbers, but there are different databases based on the various verification organizations. It is thus not an easy operation to examine whether the credit is still active in the market. This is especially challenging with over-the-counter trades (Stockholm Environment Institue & Institute, n.a.).

**Additionality** is often the core of the VCM, but there is no common understanding of the precise meaning of additionality when talking about climate change. The point of the carbon credit is that it should finance the project that leads to negative emissions (Chen et al., 2021). The credit revenue should play an essential role in making or breaking it for the project. The emission reduction will not be achieved in the absence of revenue from the sale of the credits (Michaelowa et al., 2019). However, this can be very difficult to document and make comparable (Gold standard, n.a.-a).

Microsoft highlights two significant issues that make it challenging to assess the carbon additionality in the VCM. The first is no explicit market agreement stating which baseline the removal project should be measured against (Microsoft, 2021). The baseline can be misused, and there is a risk of over-accreditation. This applies to emission reduction projects (Miltenberger et al., 2021). Secondly, there are no standardizations for how the purchase of credits should finance the removal projects. Some projects have been criticized because the credits only make up a small percentage of the total costs of the carbon removal projects. The carbon credits only finance the "last mile". This means that the projects are dependent on other sources of funding (Microsoft, 2021).

**The motive for using carbon offsetting** can be challenging to access because the market can be motivated by greenwashing rather than obtaining actual environmental benefits. The motivation behind buying carbon credits can affect how the market will lead to a positive climate impact. Criticism is directed at whether the VCM rather creates "perverse" incentives (Miltenberger et al., 2021). The fear is that companies will continue with their high-emission activities and even invest in new activities that lead to high emissions also in the future. There is an incentive to avoid a reduction in certain sectors. It is a form of greenwashing (Broekhoff et al., 2019). Today's low prices in the VCM makes it a cheap opportunity to reduce their net emissions instead of other emissions reduction measures (PwC & Zero, 2022). Science Based

Targets (SBTi) is an initiative to help companies set and reach their emission target by 2050. They are pushing the carbon reduction first and have a clear input on when to utilize carbon credits. Initiatives like this will be positive for credibility in the market and reduce the suspicion of greenwashing (Dowdall, 2021).

Trove Research has analyzed the VCM from 2010 until 2020 and concluded that the primary users were financial companies. Furthermore, it turns out that they primarily buy credits that are natural-based projects such as afforestation. This is a cheap way to call yourself net zero in communication with customers. The company appears as a green company and can attract new customers (Trove Research et al., 2021).

**Different documentation and verification standards** lead to many different ways to measure and quantify the climate effect of projects. The effects can be assessed differently in similar projects based on the chosen method and verification (PwC & Zero, 2022). This can lead to companies choosing standards that put the project in the best light and indicate the best prices. Another problem with documentation and verification is that there is no common body that adjusts and controls the way things are done. Although there are some larger organizations, such as Verra and Gold Standard, things are not controlled by an impartial third party. There are many different players in the market, and it becomes difficult for end-buyers and project developers to orient themselves and understand the differences (Kollmuss et al., 2008).

**Vintage of the credit.** As mentioned in chapter 5.1.1.5, many old credits are currently on the market at a very low price. Firms can cheaply become climate neutral this year, even though the actual storage or emissions reduction took place several years ago.

There are several issues associated with the high surplus of historical carbon credits. One of the most important is that the methods and standardizations have improved over time. Thus, one can experience that previously approved projects are no longer based on new guidelines. Therefore, the quality of older credits is often perceived as poorer (Cornillie et al., 2021). Credits with old vintage also lead to problems of additionality. It is unlikely that investment in carbon credits several years after start-up for the capture project has any bearing on whether the project has been completed or not (PwC & Zero, 2022). Nevertheless, it is important to note that the old vintage does not say anything about the quality. The quality can still be high even though the vintage is old. This assesses credits with old vintage extra difficult (Broekhoff et al., 2019).

### 5.1.1.7 Historical prices and volumes in the VCM

In recent years the market has become much more transparent, and the participating companies communicate that this is important to ensure integrity (Ecosystem Marketplace, 2021b). As shown in Figure 7 there has been a cumulative positive trend in the value of the VCM since 2005. Especially in recent years, we have seen a radical annual increase in the turnover of voluntary carbon credits. Despite the corona pandemic, which created uncertainty, the VCM set a sales record in the number of carbon credits traded in 2020. Even in 2021, a new record was set despite data only including credits sold until August in 2021. Therefore, the expectations are higher for the total volume traded in 2021 (Ecosystem Marketplace, 2021b).

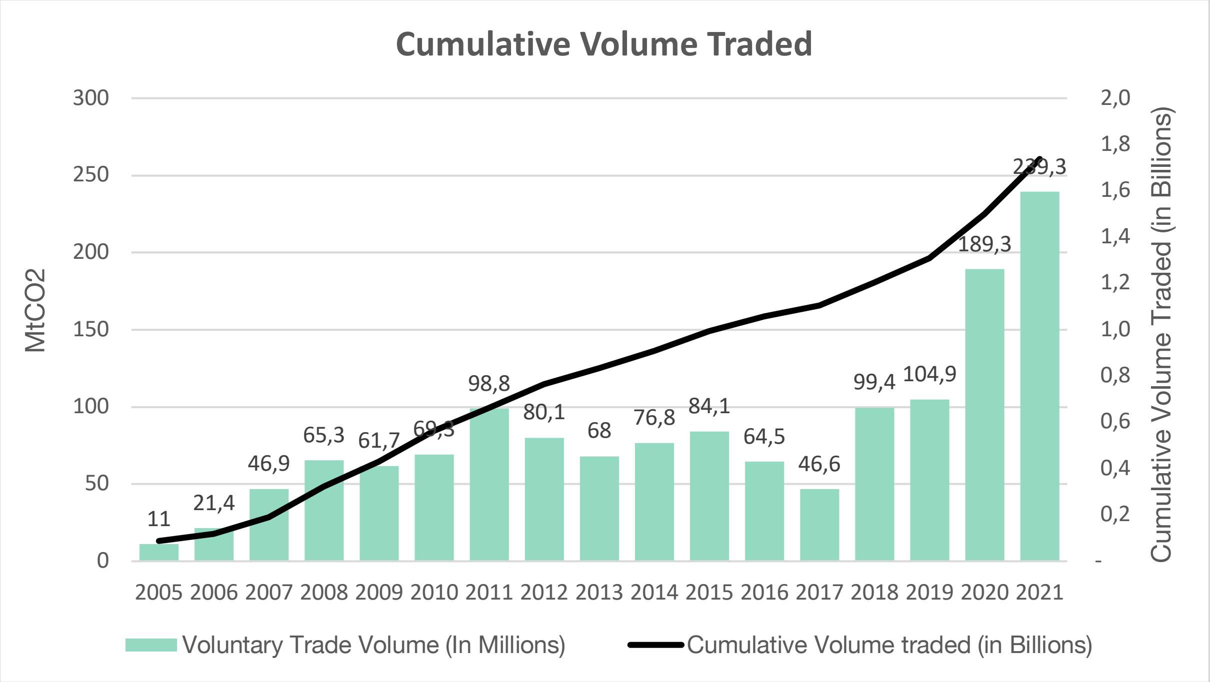


*Figure 7: Cumulative Volume traded in the VCM* (Ecosystem Marketplace, 2021a)

Figure 7 also illustrates what happens to the market when there is a lack of integrity. There was a crash in the market around the year 2016 due to a loss of credibility. Professor Cameron Hepburn explains this crash as a lack of transparency and standardization (2022). There was a lot of secrecy, and some of the project's developers cheated and sold credits of bad quality. Credits were sold larger than the capturing actually was, and there were several examples of premature release. This led to suspicion of greenwashing. Suddenly, buying voluntary carbon credit was seen as something negative. This promoted negative media coverage and publicity even though this did not apply to most projects and businesses in the market. The negative publicity and suspicion led to a lower willingness to invest in carbon credits. It is critical for the future of the VCM if this happens again (Smarter Markets, 2022). The fact that the market is now more transparent and with a high focus on information sharing makes it unlikely that this will happen in the years to come.

As shown in Figure 8 there is a trend that the price increases with increasing volume. It is difficult to predict why there was a slight dip in the prices in 2019, but by comparing this year with the EU ETS, there can be a natural explanation. 2019 is the same year as the new MSR mechanism was introduced, and prices increased. The rising price in the EU ETS may have led to a dip in the willingness to pay for a voluntary carbon credit.

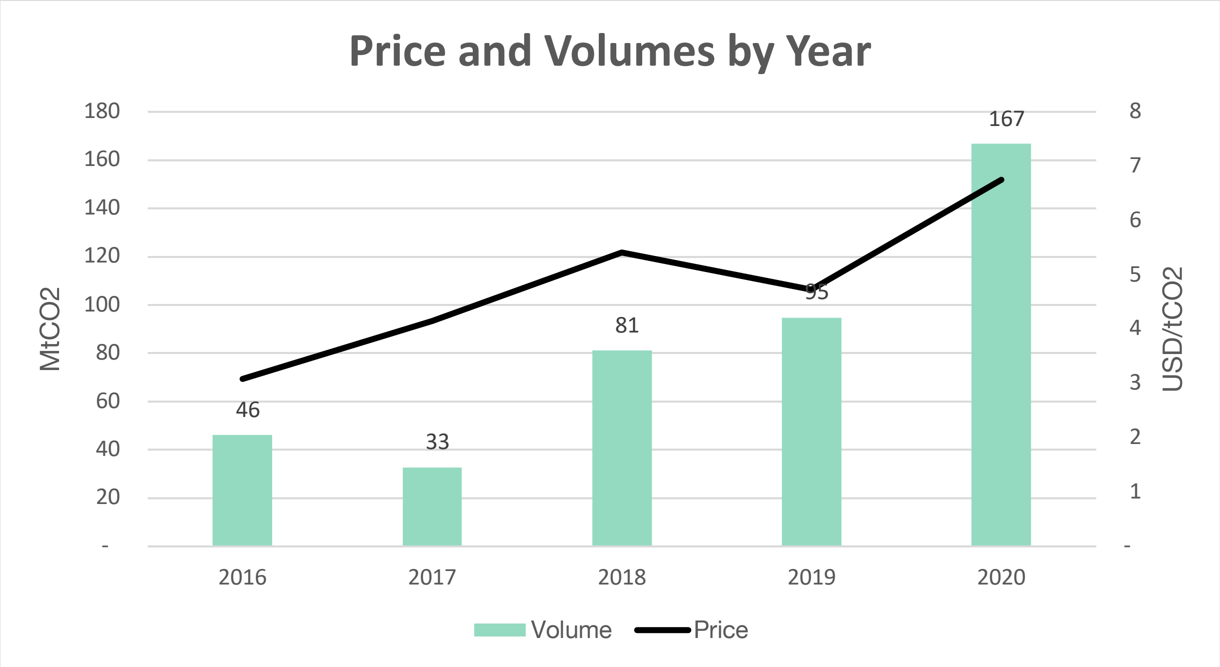


*Figure 8: Price and Volumes traded by year in the VCM (Ecosystem Marketplace, 2021b)*

Figure 8 shows only average prices in the market. There is a difference in prices based on whether it is removals or reductions projects. Historically, removal has had a price that is almost five times higher. This is probably because removals projects generally generate carbon credits of high quality. Another argument is that the volume of supply in the market is much lower, at the same time as the demand for good quality credits is high. This leads to higher prices. Table 4 illustrates the difference in price and volume over the last two years (Donofrio et al., 2021).

*Table 4: Price of removals and reductions projects (Donofrio et al., 2021)*

| | **2020** | | **2021 (Through August)** | |
|---|---|---|---|---|
| | VOLUME (MtCO2e) | PRICE (USD) | VOLUME (MtCO2e) | PRICE (USD) |
| **REMOVALS** | 9,0 | $7,93 | 5,6 | $7,98 |
| **REDUCTIONS** | 84,4 | $1,60 | 52,9 | $1,71 |

There are significant differences based on the type of project and not just whether it is removal or reduction projects. As mentioned in chapter 5.1.1.5, the carbon credit prices vary according to project type, standard, additionality, co-benefits, vintage of the credit, and risk of premature release. Figure 9 shows the variation in prices from 2016 to 2020 based on project type. The figure contains both removal, avoidance, and reduction projects but does not include prices for engineered solutions as the markets consist to a small extent of such credits today. This makes it a bit challenging to look at historical prices for engineering-based solutions.

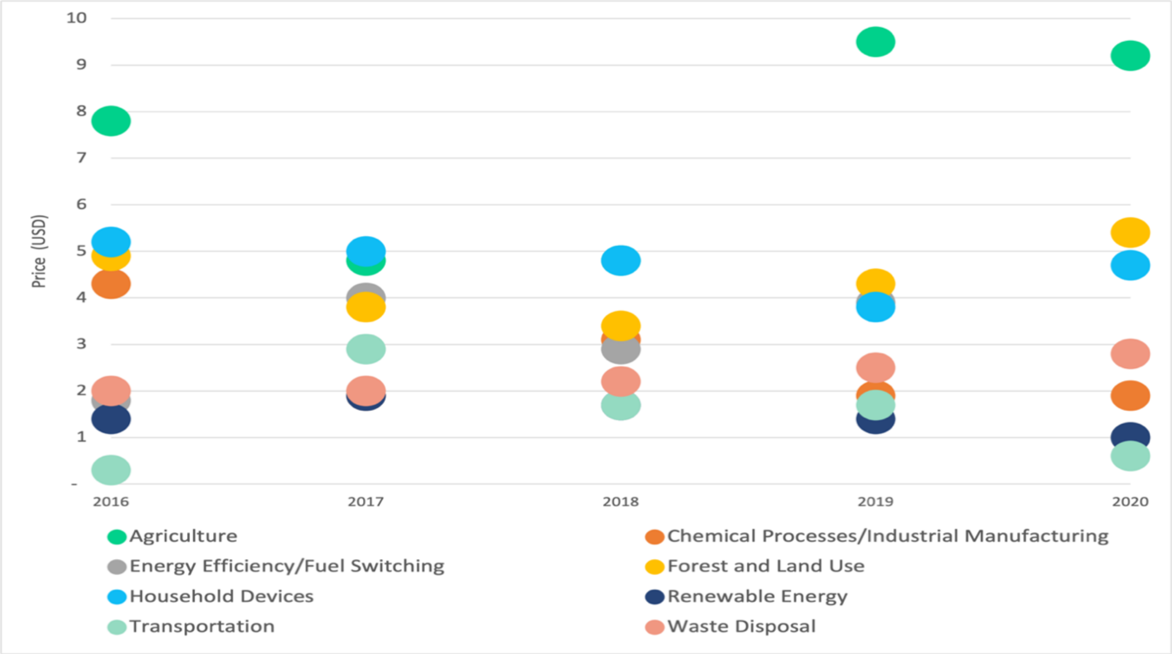


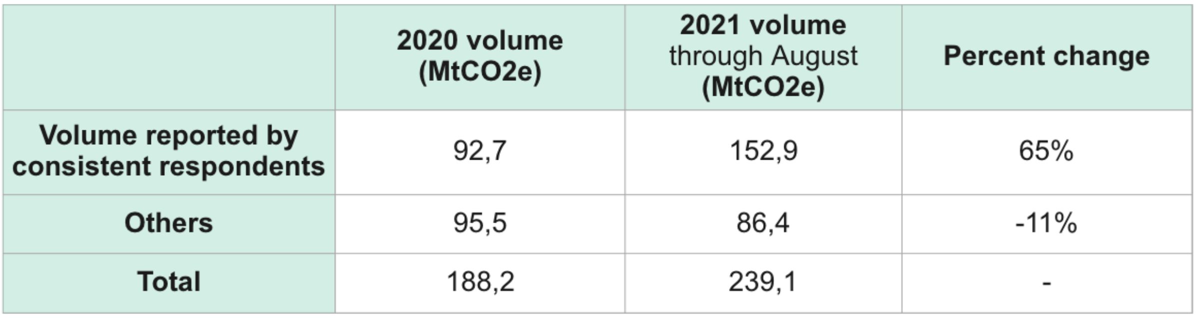
*Figure 9: Variation in prices based on project type (Ecosystem Marketplace, 2021b)*

The problem with Figure 9 is that it does not say anything about the percentage distribution between the different project types. In 2021 only 3 percent of the total distribution in the VCM was pure removal projects like reforestation. There were no credits originating from engineered solutions, and only 13 percent was a mix of removals and reduction projects like waste disposal and forest and land use. As much as 84 percent of the credits were avoidance coming from projects like renewable energy and energy efficiency (Berkely, 2022; Hong, 2022).

As mentioned in the literature review, Trove Research expects the volume to increase to 340-510 MtCO$_2$/year by 2030 from 95 MtCO$_2$ in 2020 (Trove Research et al., 2021). I assume that this applies to annual retirements in the given year. In the third quarter of 2021, the volume turns out to be approximately 103 MtCO$_2$ and has an increase of 8 percent (Trove Research, 2021b). Based on average purchases in quarters 1, 2, and 3 in 2021, I assume a volume of 35 MtCO$_2$ in quarter 4. Demand in 2021 ends up with a total of approximately 137 MtCO$_2$, thus an increase of 44 percent. If the annual increase continues at the same pace, the volume will be much higher than expected in 2030.

Data obtained from the Ecosystem Marketplace confirm the large increase from 2020 to 2021. Table 5 illustrates the large increase (Ecosystem Marketplace, 2021a). There is a fairly significant difference in the volume based on the data from Trove Research, but it turns out that the percentage increase is quite similar. There is a growing trend.

*Table 5: Volume sold on the VCM in 2020 and 2021 (Ecosystem Marketplace, 2021b)*



| | **2020 volume (MtCO2e)** | **2021 volume** through August **(MtCO2e)** | **Percent change** |
|---|---|---|---|
| **Volume reported by consistent respondents** | 92,7 | 152,9 | 65% |
| **Others** | 95,5 | 86,4 | -11% |
| **Total** | 188,2 | 239,1 | - |

Figure 10 shows how the VCM has evolved in recent months. Compared to 2020, prices have increased significantly over the past year. Priced peaked at 16 USD/tCO$_2$ in January 2022. As in the EU ETS market, there is a dip caused by Russia's invasion of Ukraine, but it seems that the situation in the market is stabilizing and that the prices are rising again (Carbon Credits, 2022).

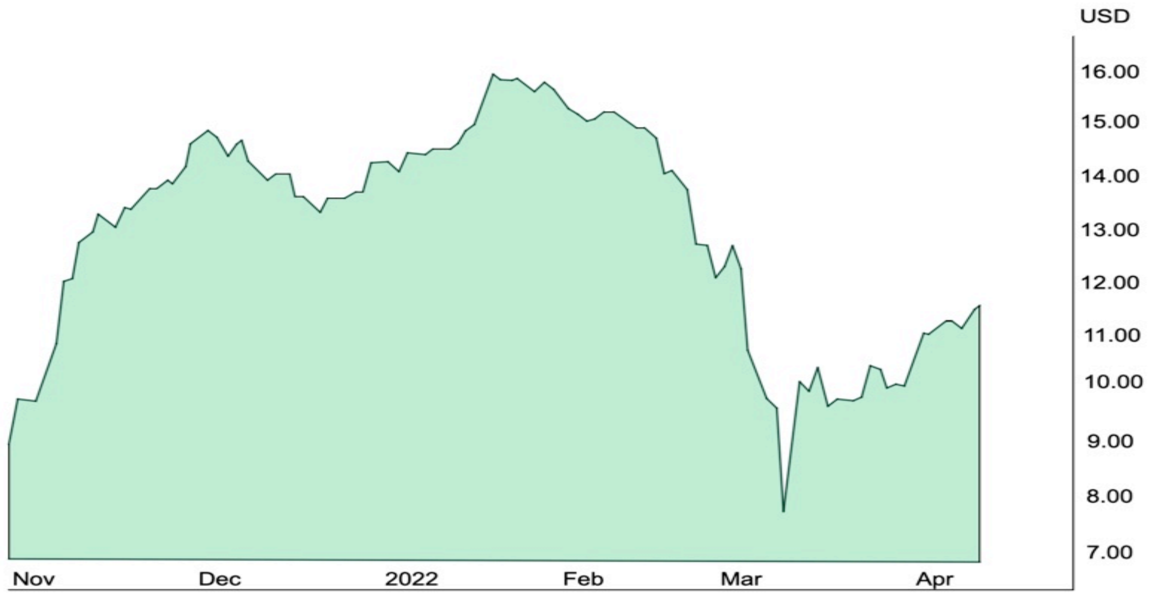


*Figure 10: Prices in the VCM (Carbon Credits, 2022)*

### 5.1.1.8 Trends and future expectations of the VCM

Many aspects may affect the VCM and how the prices of carbon credits will develop towards and after 2030. This chapter analyzes the most important drivers in the market and how they will affect the carbon credit price.

**The effect of COP26 and the Paris Agreement Article 6**

Even though the VCM is not legislated, following the completion of Article 6 rules of the Paris Agreement at COP26, it is now possible to use carbon credits from the VCM to fulfill a country's obligations under the Paris Agreement. If the rules of Article 6 are followed, activities in the VCM can help the country meet its emission target. The new rules from COP26 allow for a transaction under the Paris Agreement that may overlap, integrate, or compete with activities in the VCM (Streck et al., 2021). These changes can have major impacts on the VCM.

In article 6.2 (Cooperative approaches), there is established a framework for cooperation between countries by making it possible for one country financing climate cuts in another country without the risk of double-counting. Climate cooperation must lead to corresponding adjustment so that only the buyer or seller can count their emission cut target against the Paris Agreement. This applies to climate quotas from the EU ETS and climate credits from the VCM (PwC & Zero, 2022; Streck et al., 2021).

Through Article 6.4 (Mechanism), a new mechanism for carbon credits was established for credits that can be used to meet emission targets from the Paris Agreement. The countries must approve whether the emissions cut will be used for their reductions, whether they can be sold to others, or if it should be sold at the VCM. At the same time, the credit must be approved by an independent third party and a new Supervisory Body in the UN (PwC & Zero, 2022; Streck et al., 2021).

The risk of double-counting does not disappear completely. Figure 11 illustrates how, after the new regulations of COP26, there is still a danger of double-counting (Abettan & Hieminga, 2022).

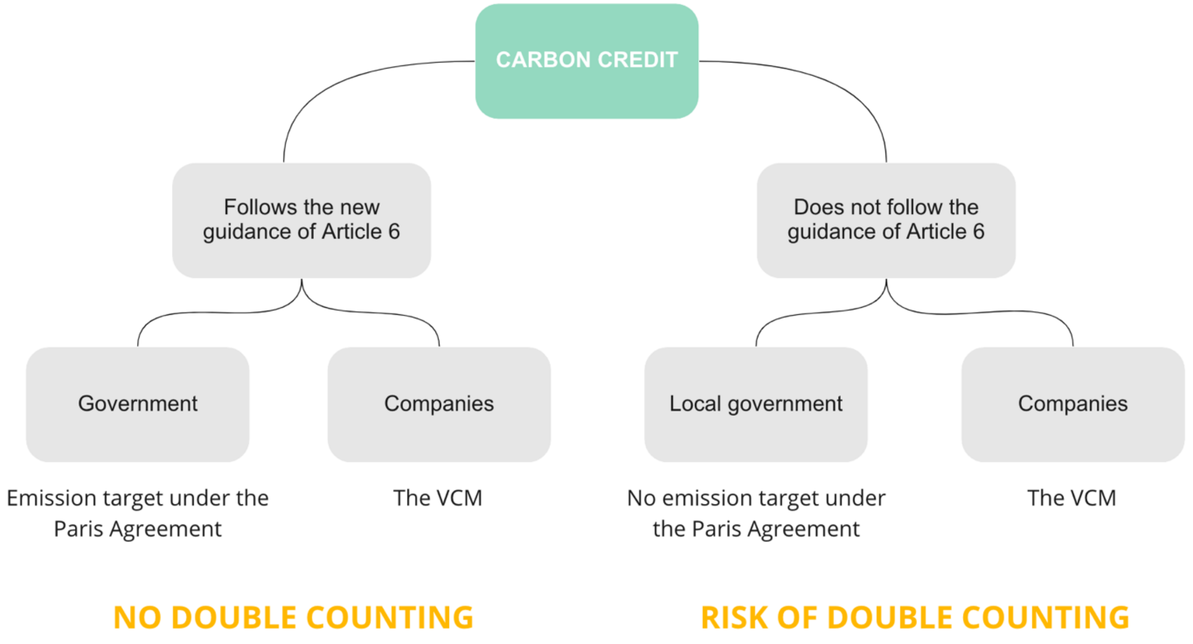


*Figure 11: The risk of double-counting. Illustration inspired by (Abettan & Hieminga, 2022)*

### Expected demand for carbon credits in the VCM by 2030

The IPCC report estimates that we need to capture up to 1,5 Gt biogenic $CO_2$ each year by 2030 (Masson-Delmotte et al., 2018). As mentioned in chapter 5.1.1.7 the volume of carbon credits sold in 2021 on the VCM was approximately 300 $MtCO_2$ (Ecosystem Marketplace, 2021a). This means that the yearly potential in the VCM can become up to five times larger by 2030. McKinsey estimates that the future demand for carbon credits will be up to 1,5-2 $GtCO_2$ in 2030 and 7-13 $GtCO_2$ in 2050. The argument is the increasing efforts to decarbonize the global economy. The estimates are based on stated demand forecasts from TSVCM in combination with the needed negative emissions in line with the 1.5-degree target. McKinsey emphasizes that the pipeline of negative emissions projects is insufficient to achieve the required negative emissions levels by 2025. Especially considering high-quality carbon removal projects like engineered solutions (Blaufelder et al., 2021; TSVCM, 2021).

The latest estimates of the demand in the VCM by Trove Research indicate that the forecast done by TSVCM are a bit optimistic. Trove Research operated with three estimates: low, medium, and high. The lowest scenario estimates a demand of approximately 0,42 $GtCO_2$, the medium scenario approximately 0,85 $GtCO_2$, and the highest scenario approximately 1,4 $GtCO_2$. These are far lower than the TSVCM. The biggest critique of the TSVCM's estimates is that they are based on what companies should do to reach the climate goals, not what they are willing to do (Trove Research, 2021a). NGFS's REMIND model estimates that to reach the emission target by 2050, approximately 1 $Gt/CO_2$ must be captured annually by 2030. This scenario is based on the idea that climate policies are introduced early and become gradually more strict (NGFS, 2021).

Shell and BCG have estimated three different market development scenarios by 2030. The scenarios are based on different assumptions about how the market will develop in the years to come. They distinguished between a global market scenario, diverged market scenario, and a linked scenario. The global market scenarios estimate demand for about 2 $GtCO_2$ each year by 2030. This scenario is based on a higher public trust in the market. This indicates full transparency and comparability in how to classify a credit. The market integrity is higher, and the market is well-functioning. They emphasize that to reach this goal, the VCM also needs to be included to help countries reach their Paris Agreement goal. As mentioned in chapter 5.1.1.8, this was the outcome of COP26, and it can be argued that we are well on our way to such a scenario. The diverged market scenario indicates a demand for carbon credits of 0,7 $GtCO_2$ by 2030. This scenario is based on a market with less global coordination and more fragmentation. These would be the market's expectations if there were no global collaboration and a lack of convergence between the compliance market and the VCM. Following the result of COP26, this scenario is less likely. The linked scenario is a combination of the first two and expects demand for carbon credits of 1,1 $GtCO_2$ by 2030. Also, in this scenario, there is a clearer link between the compliance marked and the VCM. However, the challenge in this scenario is that supply cannot keep up due to the lead time required for developing high-quality projects such as engineered solutions (Shell & BCG, 2021).

The estimates from the literature research are gathered in Figure 12 to compare the various analyses and reports. This illustrates the variation in the different estimates. That indicates that the future expected demand in 2030 varies from 0,4 to 2 $GtCO_2$. Although there is a significant gap in the expected demand, most agree that there will be significant growth in the VCM.

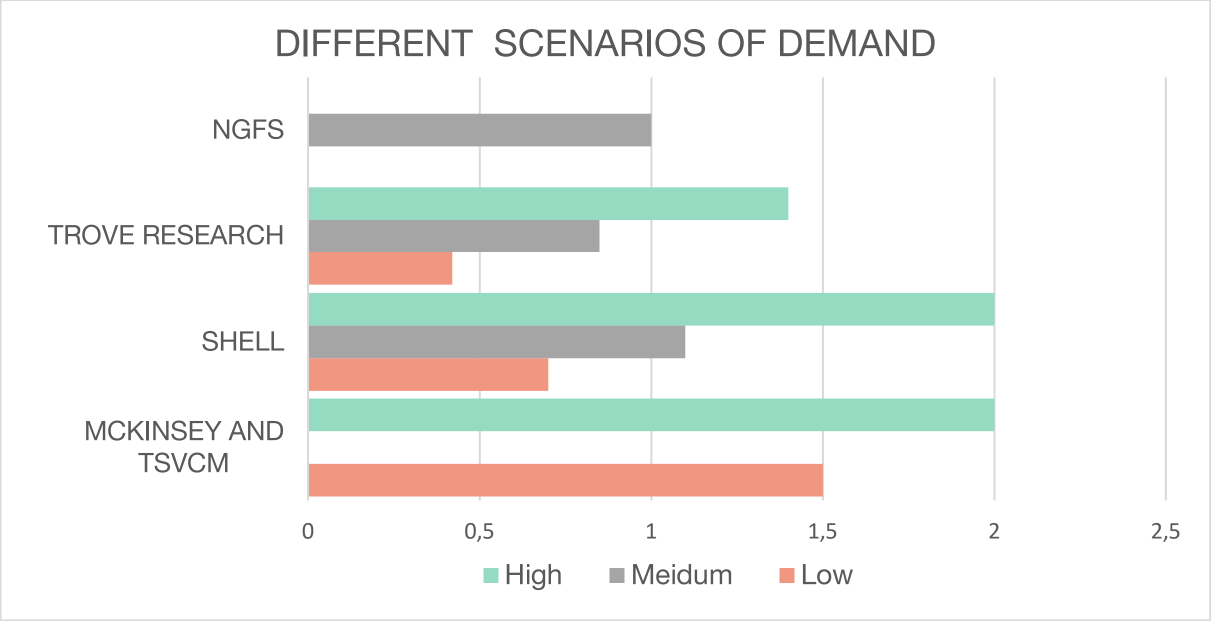


*Figure 12: Different scenarios of demand in the VCM*

A survey conducted by Zero and PwC says that 65,4 percent of the participated firms answered that they either already are net-zero or plan to be by 2030. Some participants have already mapped out how to achieve this goal, but 19,2 percent answered that they do not know how to do this yet. Carbon credits can be an important part of planning to achieve this goal. It is further stated that the goal of net-zero is the most important motivation for companies to buy carbon credits. All companies that buy credits have plans to become net-zero or are already defined as net-zero today. 64 percent of the companies surveyed said that they are already buying credits or are planning to do so in the future. In other words, only 36 percent of the respondents did not buy or plan to do so in the future (PwC & Zero, 2022). These results indicate an increasing demand in the VCM towards 2030. Appendix A illustrates the results of the survey.

Trove Research estimates that approximately 6 000 firms have set a voluntary carbon target. Of these, 534 have a goal of becoming net-zero aligned with the 1,5 degree target. Such a cut in emissions by the companies will reduce of the world's emissions by 4,5 Gt. Furthermore, 342 firms have reported slightly less ambitious targets closer to the 2 degree Celsius target, accounting for 0,9 Gt of emissions. Trove Research concludes that this is a trend that will increase. However, they point out that these are goals by 2050 and that it is unlikely that companies will need voluntary credits to achieve this in 2030. They believe that in 2030 companies will purchase voluntary credits to offset emissions in the short term (Trove Research, 2021a).

### Nature-based and engineered solutions

Nature-based solutions are the dominating trend in the VCM. The solutions are cheap, and the supply is great in 2022. At the same time, this is the most uncertain choice in terms of climate risk and human influences. Microsoft writes in their second-year report of the VCM that they experienced forest fires in one of their forest carbon projects in 2020 and experienced the great horror by using nature-based solutions. Microsoft also points out that there are clear problems with premature release and additionality in nature-based solutions. Therefore, they indicate that engineered removal will take larger market shares in the years ahead. In the years to come, nature-based solutions are still important to slow down the peak of global climate change, while the offer of engineered removal is more commercial. The nature-based solutions also often contribute to co-benefits that create local resilience against climate change (Microsoft, 2022).

There are large differences in supply, demand, and price expectations in nature-based and engineering solutions. Supply will increase for engineered solutions; however, this will take time, if the trend to favor nature-based solution continues. An analysis conducted by Shell and BCG concludes that engineered removals will grow in the years to come but will not play an important role until 2030. Nature-based solutions will account for the largest share. Shell and BCG justify this because buyers prioritize projects that meet several of the UN´s sustainability goals and have several co-benefits (Shell & BCG, 2021). Figure 13 illustrates the expected percentage distribution by supply until 2030.

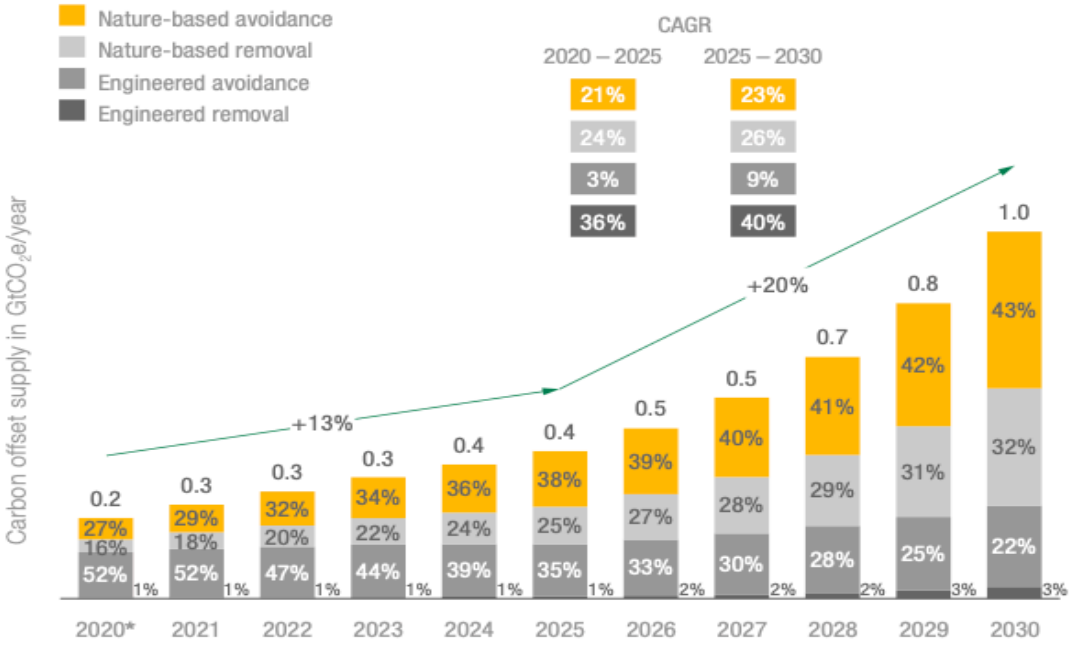


*Figure 13: Expected supply of nature-based and engineered-based (Shell & BCG, 2021)*

TSVCM carried out different distributions between carbon credits sold of natural and engineered origin. The different scenarios were based on how the market prioritizes different solutions in the years to come and how this will affect the market supply and demand in 2030 and 2050. Scenario A was based on using the current market supply, when these are used up, the new offers are based on the cheapest solutions. Scenario B prioritizes the cheapest solutions from the start. Neither scenario A nor B uses engineered solutions until after 2030. On the other hand, Scenario C is based on the supply and demand of engineered solutions already existing in 2030 but in small quantities. The modeling concludes that engineered solutions will not be fully implemented until after 2030. They nevertheless point out that we are dependent on engineered-based removal to reach the expected demand in 2050. The great growth will come in the period after 2030, and in 2050, engineered-based removal will dominate. Figure 14 illustrates how the expected distribution will be, based on the different scenarios. In all scenarios, the engineered solutions will dominate in 2050 (TSVCM, 2021).

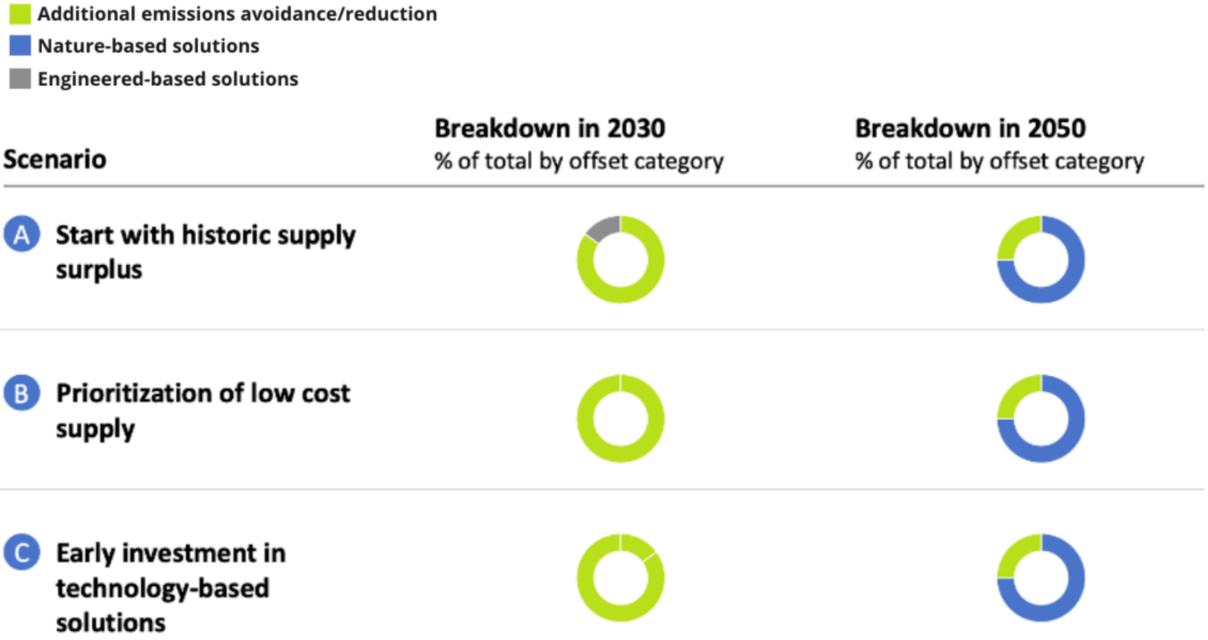


*Figure 14: Expected distribution of nature-based and engineered-based solutions*

**Expected supply of carbon credits in the VCM by 2030**

Now that expected demand has been examined, another important aspect is how the future supply is. It does not help to have high demand in a market if there is no supply. TSVCM and McKinsey found that the practical potential of carbon credits supply was up to 8-12 $GtCO_2$ each year by 2030. The practical potential disregarded the markets, political, financial barriers, and risks. Using the feasible filter, the supply can be 1-5 $GtCO_2$ per year by 2030. The feasible filter's modeling is more likely to occur (Blaufelder et al., 2021; TSVCM, 2021).

TSVCM models that the distribution of practical potential of carbon credits supply includes 3,7 $GtCO_2$ avoided natural loss, 2,9 $GtCO_2$ nature-based solutions, more than 0,2 $GtCO_2$ emissions avoidance and, 1-3,5 $GtCO_2$ removed by engineering solutions. The engineering solutions include booth biogenic CCS and DACCS (TSVCM, 2021). Although this is based on practical potential, it still shows the distribution between the various solutions. This strengthens the theory that nature-based solutions will dominate in the years ahead, but the market for engineer-based solutions will grow rapidly after 2030.

#### 5.1.1.9 Expected carbon prices

The large variation in price in different project types makes it challenging to estimate future prices. The modeling carried out by TSVCM resulted in a price variation of 10-50 USD/$tCO_2$ for nature-based solutions. The engineered solutions are expected to have a higher price of between 100-200 USD/$tCO_2$. Here the price will vary depending on BECCS or DACCS solutions (TSVCM, 2021).

Analyses conducted by Trove Research and UCL concluded that higher prices are required to have the desired climate effect. Just not as high as the TSVCM. In 2030, they estimate that prices will be between 20-50 USD/$tCO_2$. This interval is based on a VCM that works efficiently, and the forecast is optimistic. They emphasize that this is not the most likely price forecast, yet the interval is noticeably lower than the scenario of TSVCM (Trove Research, 2021a).

Trove Research points out that companies will be willing to pay the high price estimated by TSVCM if there is a particularly good or innovative project. However, there is great uncertainty about those types of high-quality solutions. There are not many of these in today's market, and the engineered solutions have therefore not been tested on the market. This makes it very difficult to predict the future. There has previously been a problem with high prices in the EU ETS and the uncertainty this creates with the additional cost for companies in Europa. Therefore, it can seem naive to think that companies will be willing to pay such a high price in a voluntary market (Trove Research, 2021a).

As mentioned in chapter 5.1.1.8, it is expected that there will be a difference in demand and supply based on whether it is natural-based or engineered solutions. This will lead to different prices for carbon credit origin from natural and engineered. Trove Research says that:

> *"High environmental integrity comes at a price."*

It is more likely that a high-priced carbon credit belongs to a truly additional project. The higher the price of the carbon credit is, the greater the probability is that the project would not have taken place without the carbon credits. Another important point is that the lover cost options, as natural solutions, will be used up over time. There is a limit to how much avoided emissions it is possible to create based on a company's baseline or how much a tree caches over its lifetime. This combination will, over time, drive the credit prices up in the VCM (Trove Research, 2021a).

The research company BloombergNEF published a "Long-Term Carbon Offset Outlook 2022" (2022). The report tried to analyze the outcome of the VCM relative to the rapidly expanding universe of sustainability goals. They analyzed three different scenarios based on how the VCM will develop in the years to come. Figure 15 illustrates the variation in expected prices in the three scenarios. This analysis emphasizes how much influence the development of the market has on the expected price (BloombergNEF, 2022).

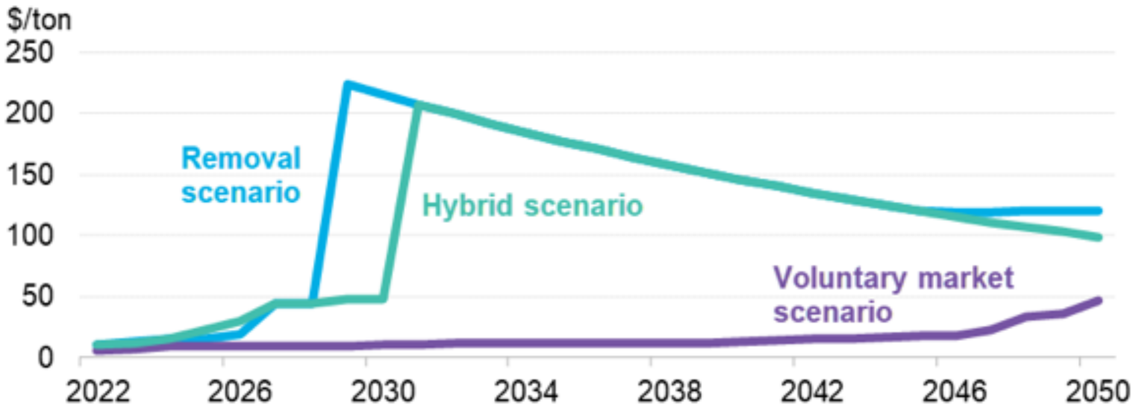


*Figure 15: Price scenarios by BloombergNEF (2022)*

The voluntary scenario is based on a business-as-usual assumption. The VCM stays at the same level as today. All types of projects are available on the market reducing and removing emissions. Due to little market regulation, a price of 11 USD/t$CO_2$ by 2030 is expected. These low prices lead to little additionality and actual environmental benefits. The market will thus never completely take off. The removal scenario is based on only removal projects in the market, such as nature-based and engineered solutions. Companies still run the market, but the focus is now to reach net-zero. The large price jump in 2030 result from the supply estimated to be smaller than the demand. In this scenario, the prices are expected to be 224 USD/t$CO_2$. Prices will adjust lower as BECCS and DACCS become more commercial solutions. There is thus a percentage decrease in this market rather than a percentage increase like in the commercial markets. In a market with such high prices, the actual environmental benefit and integrity in the market are much higher. The hybrid scenario is based on a gradual development of the VCM. Here the market goes from a voluntary removal market for companies to a removal market for countries. This presupposes a global quota market that encourages countries to buy emission reductions from each other. The prices will only rise to 48 USD/t$CO_2$ by 2030 but will increase to 217 USD/t$CO_2$ the following year. This is still a large price jump, and the scenario assumes that there will be significant changes in the VCM concerning the current market (BloombergNEF, 2022).

To make the estimates from the different analysts comparable and usable in later calculations, all estimates have been converted to NOK 2022 prices. Table 6 summarizes the various estimates and main arguments.

*Table 6: Price scenarios summarized for the VCM*

| Source | Low forecast prices by 2030 | High forecast prices by 2030 | Main arguments |
|---|---|---|---|
| **TSVCM (Nature-based)** | 100 NOK/tCO2 | 500 NOK/tCO2 | • The new emission target<br>• Technologies cost<br>• Demand nature-based |
| **TSVCM (Engineered-based)** | 1000 NOK/tCO2 | 2000 NOK/tCO2 | • Demand engineered based solutions |
| **Trove Research** | 175 NOK/tCO2 | 400 NOK/tCO2 | • Willingness from companies<br>• Reach the climate goal<br>• Integrity comes at a price |
| **BloombergNEF** | 100 NOK/tCO2 | 1975 NOK/tCO2 | • The future market mechanisms |

#### 5.1.1.10 Price scenarios

Several price scenarios are set up based on expectations and certain assumptions grounded in this chapter. There are only estimates of the price for engineered solutions since that is relevant for CCS at a waste incineration plant. The price scenarios try to reflect the uncertainty in the market. Regardless of the scenario, the price is expected to increase at the same rate as the EU ETS prices, which is 4,2 percent per year. The different price scenarios are listed in Table 7.

*Table 7: Price scenarios for engineered solutions in 2030*

| PRICE SCENARIO | CARBON CREDIT price for Engineered by 2030 |
|---|---|
| NO LONGER A VCM | 0 NOK/tCO2 |
| LOW | 300 NOK/tCO2 |
| BASE | 948 NOK/tCO2 |
| EU ETS LEVEL | 1475 NOK/tCO2 |
| HIGH | 1999 NOK/tCO2 |

**No longer a VCM** scenario indicates that there is no longer a voluntary carbon market. There will no longer be possible to sell carbon credits in the market. The price is therefore set to 0.

**The low price scenario** assumes that there will be a homogenous market with no price difference between natural and engineered solutions. There will be a fixed price on the credits. Therefore, it is assumed that the price will be in line with the natural solutions. The price is calculated by taking the average of the lowest and highest value for nature-based solutions calculated by TSVCM. This analysis is used because this is the only one that distinguishes between natural and engineering solutions at the expected price. The low-price scenario indicates a credit price of 300 NOK/t$CO_2$.

**The base price scenario** is the most likely outcome of the carbon price of engineered solutions. The price is calculated as an average of the various estimated prices from chapter 5.1.1.9. Prices that only include natural solutions are not included in this calculation. This indicates a well-functioning market where the credibility is high and the market is more regulated. There is a distinction between natural and engineering solutions. The base price scenario indicates a credit price of 948 NOK/t$CO_2$.

In the **EU ETS level scenario**, the price of a carbon credit equals the price in the EU ETS. It would be natural if these prices followed each other. Also a distinction is made between natural-based and engineered solutions in this scenario. The EU ETS level scenario indicates a price of 1 575 NOK/t$CO_2$.

**The high price scenario** is the most optimistic scenario. Also, in this scenario, there is a distinction between nature-based and engineering solutions. The prices of carbon credits are set higher than the EU ETS. The high price scenario indicates a price of 1 999 NOK/t$CO_2$.

## 5.2 Profitability assessment

The purpose of this chapter is to analyze the second sub-question announced in chapter 1.2:

1. *Will it be profitable for a waste incineration plant to invest in carbon capture and storage based on income from carbon credits origin from capturing the biogenic emissions?*

Following the approach outlined in chapter 4, I present the assumptions, the result from the profitability analysis and, the sensitivity analysis.

### 5.2.1 Budgeting of cash flow

In this subchapter, the cash flow will be estimated using a most likely base scenario for the waste incineration plant. The estimates of the income and saved costs are calculated based on the result of the market analysis in chapter 5.1.

#### 5.2.1.1 Analysis period

Neither the CCS technology nor the VCM are very mature. Thus, to include development features for both the technologies and the VCM, the analysis period is set from 2030 to 2055. To include the uncertainties associated with the long-time horizon of the investment project, the analysis period is 25 years and is equal to the plant's service life. The service life of a carbon capture plant is estimated to be 25 years (Gassnova, 2020a). Since the estimated lifetime and the analysis period are equal, the residual value is zero (Direktoratet for økonomistyring, 2018). Gassnova disregarded the decommissioning of the plant in their calculations and estimated a residual value equal to zero (Gassnova, 2020a; Gassnova, 2020b). The delivery time of the plant is estimated to be approximately a year, this varies depending on the facility. The investment year is set for 2030, and the start of operations is estimated in 2031.

#### 5.2.1.2 Cost of the value chain with CCS

Auden et al. performed all cost calculations and give a Levelized cost of carbon capture and storage (2022). They are stated in fixed NOK 2022 prices. The cost estimates are based on a plant that can use heat integration in the catch process. The costs are estimated in intervals. The base scenario is based on the mean value between the lowest and highest estimate. The value chain calculations are assumed based on 25 years of lifetime and a discount rate of 7 percent. The number of tons caught is estimated to be 100 000 per year. Figure 16 illustrates the value chain of CCS at a waste incineration plant. The content of the figure is described more clearly in the text below.

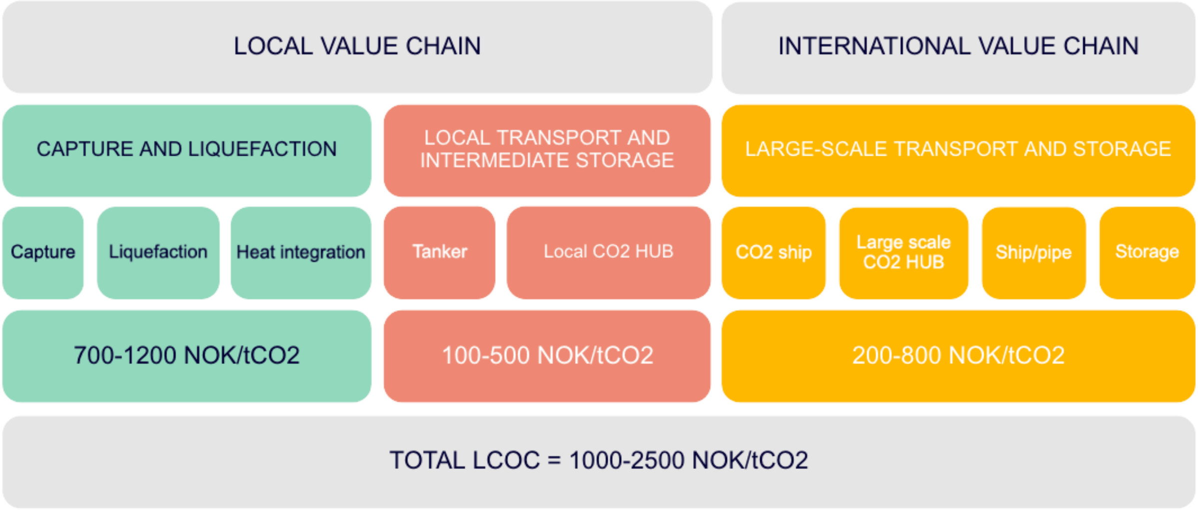


*Figure 16: Levelized Cost of Carbon Capture and Storage (Aspelund et al., 2022)*

As mentioned earlier, I focus on the incremental cash flows stemming from a decision to invest in carbon capture and cover the cost of transport and storage of $CO_2$; that is, the difference in cash flows from a waste incineration plant with and without CCS. The actual incineration of the waste is not included in the costs associated with CCS.

**The local value chain** for the CCS involves the processes at the waste facility and until the final port before the North Sea. This part involves significant investment costs of the project and annual operation and maintenance costs. The first Levelized cost involves the local value chain and activities at the waste incineration plant. This includes the capture and liquefaction of $CO_2$ with heat integrated. The cost would have been higher if the heat from the incineration process was not integrated. The Levelized cost of catch and liquefaction is estimated to have a value of 700-1200 NOK/$tCO_2$. The local value chain also includes local transport and intermediate storage. Here it must be invested in a local $CO_2$ hub by the sea and tanker truck. This is estimated to have a Levelized cost of between 100-500 NOK/$tCO_2$. The local value chain's total Levelized cost is 800-1700 NOK/$tCO_2$.

**The international value** chain includes large-scale transport and final storage in the North Sea. This includes ships transporting the stored $CO_2$ from the local port to the port with a large-scale $CO_2$ hub. Then it is transported by pipe or ship to the final storage in a reservoir. The international value chain does not require large investments but high annual costs as this is a service that is purchased annually. The expected Levelized cost is between 200-800 NOK/t$CO_2$.

According to the annual report of Aker Carbon Capture 2021, they have begun to see benefits from learning by doing and assume that further digitalization will contribute to reduced costs. They estimate that they will cut their investment costs by 50 percent by 2025 (Aker Carbon Capture, 2022b). Due to increased prices of raw materials and a lot of uncertainty in the worldwide economy (SSB, 2022), I expect the investment costs to be reduced by 20 percent by 2030. These cost reductions only include the investment cost. The annual operation and maintenance costs will be at the same level. The costs may stay at the current level because reduced investment costs can lead to the need for more employees, more frequent regulations, and general changes in annual costs. In the absence of an estimated future cost reduction in the international value chain, the estimated cost is set equal to the current level.

In the base scenario, the total LCOC at a waste incineration plant is assumed to be 1 750 NOK/t$CO_2$.

#### 5.2.1.3 The distribution of costs

As described in chapter 4.2.1.2, the distribution between the capital cost and the operation and maintenance cost was mapped by literature. The distribution has been found using Gassnova's reports from the CCS projects Fortum Oslo Varme and Norcem. These cost estimates are outdated and too high, but the relationship between the investment in year 0 and the annual operation and maintenance costs are assumed to be quite similar. Gassnova has published two reports of the facilities: Norcem and Fortum Klemetsrud. In Gassnova's final evaluation report, the cost estimates are only based on the local value chain and exclude the international value chain. The costs from the international value chain have already been estimated in annual cost, so I just need to distribute the costs in the local value chain (Gassnova, 2020b). Table 8 shows the costs for CCS at Norcem and Fortum Klemetsrud.

*Table 8: Cost for CCS at Norcem and Fortum Klemetsrud (Gassnova, 2020b)*

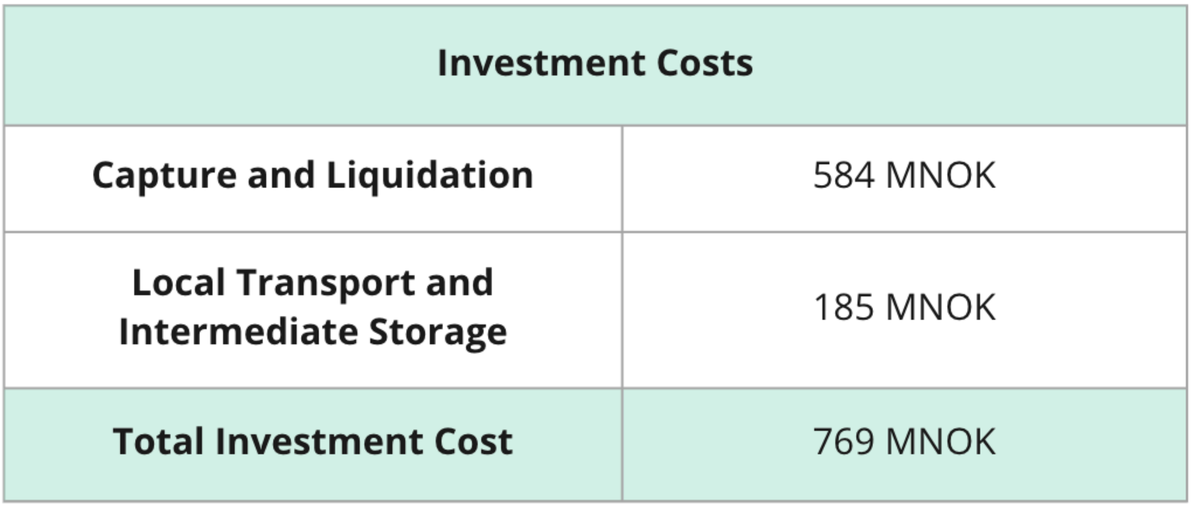
| | Investment Cost | Operation and Maintenance Cost |
|---|---|---|
| **Norcem** | 2723 MNOK | 107 MNOK/annually |
| **Fortum Klemetsrud** | 4276 MNOK | 216 MNOK/annually |

Investment costs are translated into annual capital costs by using the formula of annual capital cost described in chapter 4.2.1.2. Based on the cost distribution stated in the reports from Gassnova, the average distribution is that the annual capital cost account for 66 percent, and annually operation and maintenance cost account for 34 percent of the total costs (Gassnova, 2020b).

#### 5.2.1.4 Investment costs

After finding the distribution between the percentage distribution of the costs, the annual investment costs for capture and liquidation are estimated to be 502 NOK/t$CO_2$ each year. The total investment cost in year 0 is 584 MNOK for a plant that catches 100 000 tones per year. The annual investment costs for local transport and intermediate storage are estimated to be 158 NOK/t$CO_2$ each year. Converted to total investment cost in year 0, this is 185 MNOK. Therefore, the total investment cost of the CCS is estimated to be approximately 480 MNOK for the waste incineration plant. Table 9 summarize the expected investment cost for the plant.

*Table 9: Investments costs*



| Investment Costs | |
|---|---|
| **Capture and Liquidation** | 584 MNOK |
| **Local Transport and Intermediate Storage** | 185 MNOK |
| **Total Investment Cost** | 769 MNOK |

#### 5.2.1.5 Operation and maintenance costs

The annual operation and maintenance costs for the capturing and liquidation are estimated to be approximately 323 NOK/t$CO_2$ annually. This indicates a yearly cost of 32 MNOK for the plant. The annual operation and maintenance cost for the local transport and intermediate storage is a bit cheaper, with an estimated cost of 102 NOK/t$CO_2$ annually. This indicates an annual operation and maintenance cost of 10 MNOK for the plant. Large-scale transport and storage costs are already based on an annual cost and are estimated to be 500 NOK/t$CO_2$ annually. This indicates an annual cost of 50 MNOK for the plant. The total annual costs and operation and maintenance of the CCS for the waste incineration plant are approximately 92 MNOK each year and are summarized in Table 10.

*Table 10: Annually and operation and maintenance costs*

| **Operation and Maintenance Costs** | |
|---|---|
| Capture and Liquidation | 32 MNOK/annually |
| Local Transport and Intermediate Storage | 10 MNOK/annually |
| Large-scale Transport and Storage | 50 MNOK/annually |
| **Total Annually and Operation and Maintenance Costs** | **92 MNOK/annually** |

#### 5.2.1.6 Saved costs

The investment of CCS will lead to extra revenues from the sale of carbon credits and saved costs. Future taxes and prices of quotas that can affect the waste industry are therefore mapped.

Whether the EU's draft proposal about including waste incineration in the EU ETS mentioned in chapter 3.4.1 includes the biogenic and the fossil emissions is not communicated. Therefore, it is assumed in further analyses that the future EU ETS will only include fossil emissions. As mentioned in Chapter 3.4.1, there are also proposals from the EU to increase the annual reduction factor for the cap in the EU ETS market. In this analysis, it is therefore assumed that the quota price increase by 4,2 percent each year (European Commission, 2021b). Since the cash flow is in real terms, the EU ETS price needs to increase in real terms. Inflation must be deducted from the price increase, and the EU ETS price will increase by 2,2 percent yearly in the cash flow.

A tax on waste incineration was recently introduced in Norway. This tax applies to the fossil part of the emissions and costs 192 NOK/t$CO_2$ released. For the tax to only include the fossil part of the emissions, the total emissions must be multiplied by a factor of 0,5498. This standard applies to all waste incineration plants in Norway (Skatteetaten, 2021).

The 2022 tax is calculated based on current $CO_2$ prices and corresponds to 25 percent of today's $CO_2$ prices. The Norwegian Government's climate plan for 2021-2030 states that they want to gradually increase the general $CO_2$ price. The Government intends to increase the general $CO_2$ tax to 2000 NOK/t$CO_2$ in 2030 (Avfall Norge, 2021; Meld. St. 13 (2020-2021)). Since the emissions to the waste incineration plant consist of both biogenic and fossil emissions, this will, in theory, means a price of 1 000/t$CO_2$ emitted. The Government's goal is that the price from the EU ETS and the tax on the waste incineration will have a total price of 2000 NOK/t$CO_2$ (Meld. St. 13 (2020-2021)). The total price of the EU ETS and incineration tax is therefore expected to be 2000 NOK/t$CO_2$ in the base scenario. The $CO_2$ tax is expected to grow in line with the EU ETS, and it is assumed that the $CO_2$ tax will increase by 2,2 percent each year. Table 11 shows the estimated saved cost in 2031. It is important to note that the saved costs will increase by 2,2 percent each year after 2031. The table is just valued for the first year of operation.

*Table 11: Saved costs*

| **Type of Saved Cost** | **Saved Costs in 2031** |
|---|---|
| EU ETS | 56 MNOK/annually |
| CO2 TAX | 56 MNOK/annually |
| **Total Saved Cost** | **112 MNOK/annually** |

#### 5.2.1.7 Income

The extra revenue for the waste incineration plant that accrues due to the investment in CCS is from the sale of carbon credits. In the base scenario, an engineered carbon credit price is estimated to be NOK 948 per t$CO_2$. Since the VCM and the EU ETS are expected to grow relatively similarly, an annual increase in price is set equal to the increase in the EU ETS by 2,2 percent annually. Table 12 shows the estimated income from selling carbon credits in the first year of operation.

*Table 12: Income*

| Type of Income | Income in 2031 |
|---|---|
| Carbon Credits | 45 MNOK/annually |
| **Total Income** | **45 MNOK/annually** |

#### 5.2.1.8 The waste mix – share of biogenic emissions

As mentioned in chapter 1, the waste sent for incineration consists of approximately 50 percent biogenic and fossil emissions (Torvanger, 2021). In the base scenario, I used the same distribution factor used by the tax authorities of Norway to calculate the $CO_2$ tax. The factor indicates that 54,98 percent are fossil, and the remaining 45,02 percent are biogenic emissions (Skatteetaten, 2021). This factor is identical to the standard carried out by the Norwegian Environment Agency for household waste (Miljødirektoratet, 2020).

#### 5.2.1.9 Discount rate

The discount rate is set according to recommendations by the Norwegians Government's "Rundskriv R" and is risk-adjusted in the base scenario. The risk-adjusted interest rate recommended is 4 percent (Finansdepartementet, 2021). Variations in the amount of waste can affect the plant's profitability because the fixed costs can be divided by several tons of waste. The waste volume will vary with the world's economic conditions and thus contribute to systematic risk. I consider the risk to be small to average. This gives a beta equal to one, and the discount rate for the project is set to 4 percent (Bøhren & Gjærum, 2020).

#### 5.2.1.10 Cash flow statement

Based on the assumptions and expectations mentioned in the subchapters above, the cash flow is set up at fixed prices. The incremental cash flow associated with investing in CCS at a waste incineration plant is presented in Figure 17. The cash flow is positive already in year 2. The figure illustrates how the income and the saved costs increase each year.

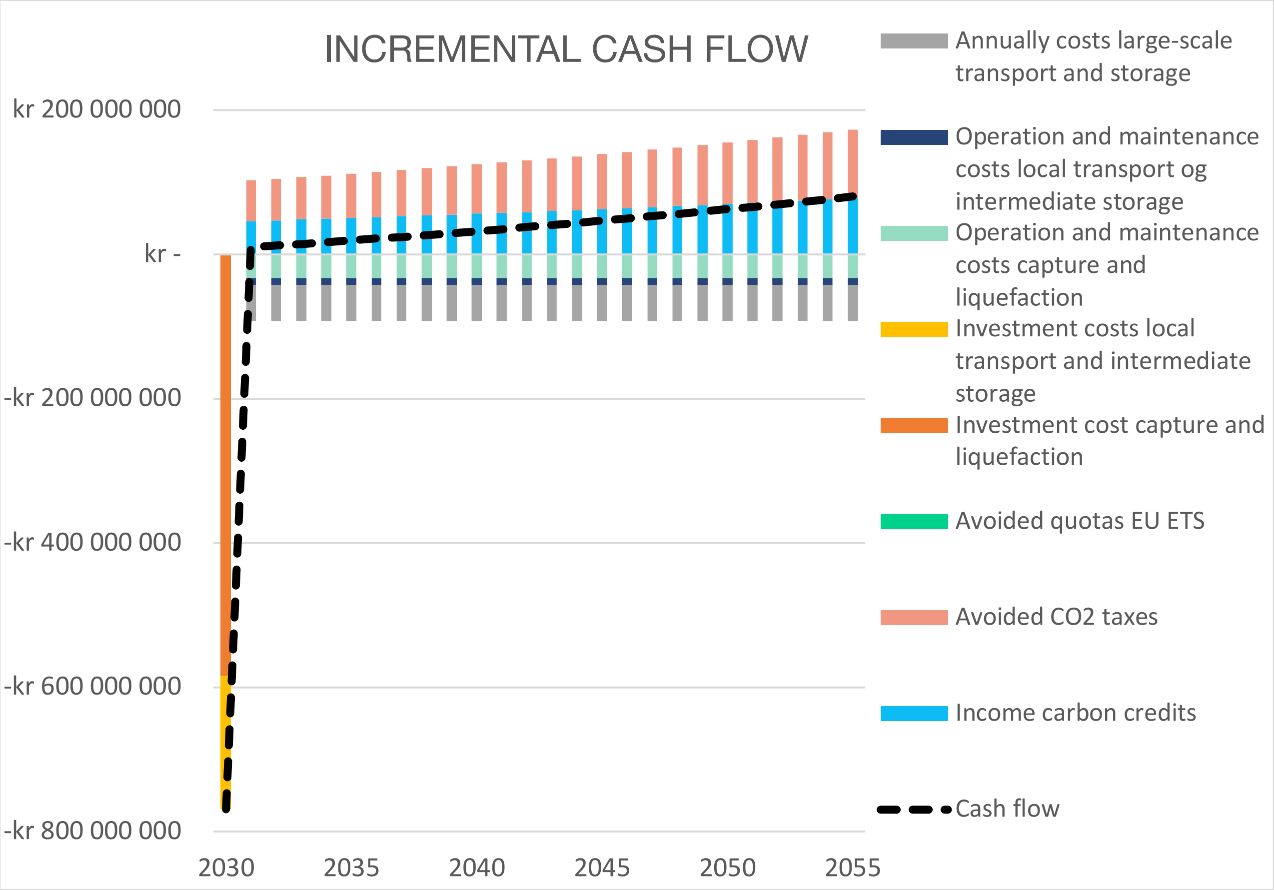


*Figure 17: Incremental cash flow for investing in CCS at a waste incineration plant*

### 5.2.2 Profitability Analysis

Table 13 shows the NPV and the IRR of the project. With given assumptions, the base scenario gives a positive NPV of 818 MNOK, while the IRR is 11 percent. The positive NPV and an IRR higher than the discount rate indicate that the project is profitable.

*Table 13: Profitability assessment: base scenario*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | 818 MNOK |
| **IRR** | 11 % |

### 5.2.3 Sensitivity analysis

The profitability assessments conducted in chapter 5.2 indicate that the project is profitable and that waste incineration plants should invest in CCS. However, the analysis is based on several assumptions, and several uncertain aspects that need to be clarified and mapped.

This subchapter examines how sensitive the project's NPV is to change. A star chart has been made to map which variables affect the NPV to the greatest extent. Subsequently, various scenarios are examined and analyzed. The risk-free discount rate is set to 2 percent, in the sensitivity analysis.

#### 5.2.3.1 Star chart analysis

Figure 18 shows how the NPV is affected by the percentage change in different variables based. The selected variables are commented further in this subchapter and are considered the most interesting variables of the analysis.

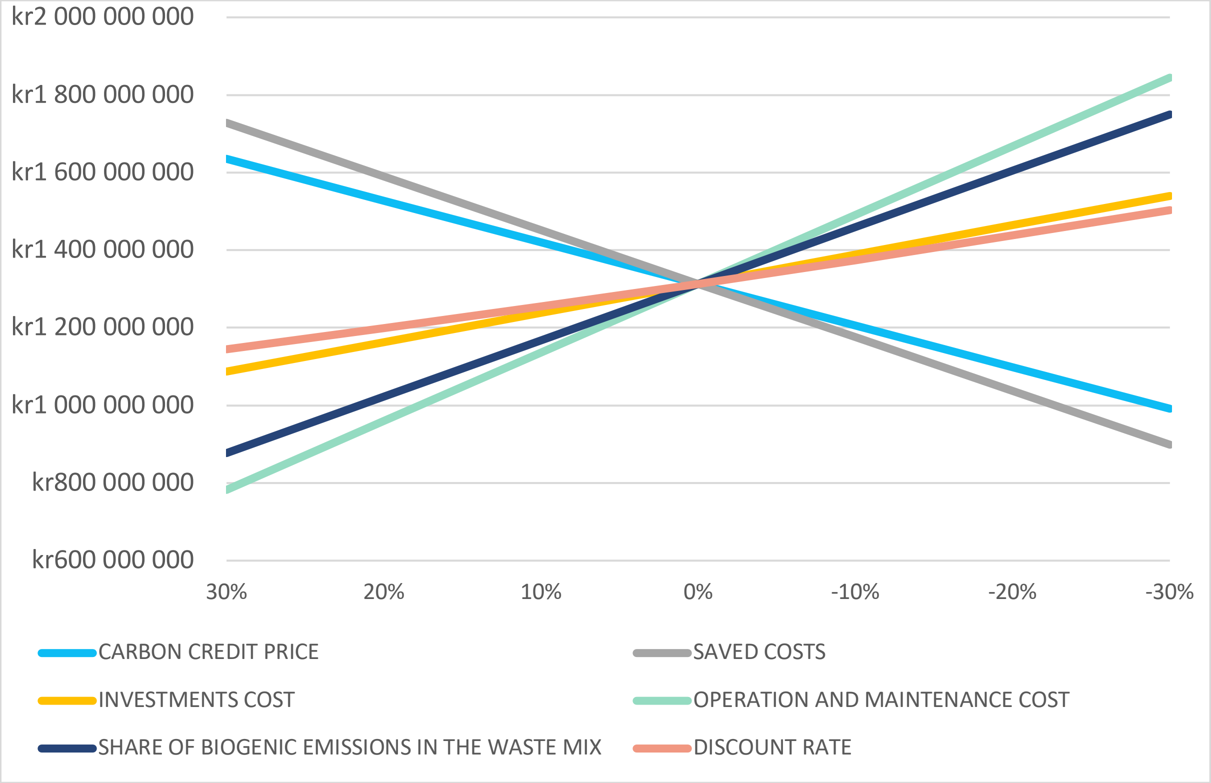


*Figure 18: Star chart: base scenario*

**Investment costs**

The estimated investment costs for the CCS plant are some of the most uncertain estimates in the analysis. According to the star chart analysis (Figure 18), investment cost has less to say for the project's profitability. If the investment cost increases by 10 percent, the NPV will decrease by 6 percent. Since the estimated investment cost is so uncertain, it is essential that the variable does not affect the NPV to a great extent. Trove Research concludes that the most uncertain factors for the investment costs concern the size of the plant, chosen CCS technology, and the choice of transport method (Trove Research et al., 2021).

The choice of transport method can affect the size of the investment costs and the annual operation and maintenance cost. This applies to investments related to the local value chain. A higher investment cost will be associated with transport via pipes to the local port than if the captured CCS is transported by tankers. Pipes in the ground will have a much higher investment cost than transport by tanker. Pipes can give large investment costs in year 0 and low annual operation and maintenance cost, while tankers provide lower costs in year 0 and higher yearly operation and maintenance costs. Therefore, it is important to note that the investment costs may be higher than in this thesis if the transport method is by pipe and not by tanker.

**Operation and maintenance costs**

According to the star chart analysis, operation and maintenance costs affect the project's profitability to the greatest extent of the selected variables. With an increase of 10 percent in annual operation and maintenance costs, the NPV decreases by 13 percent. Trove Research introduces the following aspects that can affect the yearly operation and maintenance costs: share of biogenic emission in the waste mix, choice of transport, distance to the local and final port, and type of long time storage (Trove Research et al., 2021).

As mentioned earlier, the choice of transport method has a lot to say for the investment costs, this choice will also have a significant impact on the annual operation and maintenance costs. Another factor that affects these costs is the location of the waste incineration plant and how far it must be transported before it reaches the local port. The choice of fuel in the tanker and the ship will affect the annual operation and maintenance cost.

The annual costs associated with the international value chain are also very uncertain. This is a service purchased in the market and includes the costs of transport from the local port to the final port, temporary storage at the final port, and transportation from the final port and out to the storage site in the North Sea. The choice of ships by the seller of the service and the distance to the final port will greatly affect the costs. It is uncertain what the price of this service will be in the future as the offer by now is a type of monopoly market. There is no competition in the market related to the delivery of permanent storage because there is only one project that delivers this service in Norway. In theory, they can almost set the price as high as they want.

Another factor that will affect the annual operation and maintenance cost of the plant is whether it applies an integrated heating technology or not. An integrated heating technology means that the heat from the waste incineration is used in the carbon capture process. Some incineration plants already use waste heat in internal or external projects such as district heating. However, not all waste incineration plants have this system integrated. They must then use electricity or gas to produce the heat needed. This will make the project sensitive to changes in electricity and gas prices. It is assumed in this thesis that such a system is integrated. The costs will thus be higher in a system without it.

**Carbon credit prices**

It appears in the star chart analysis that the project's profitability is quite sensitive to changes in the carbon credit price. A 10 percent price increase for carbon credits will increase the NPV by 8 percent. This indicates that the income from the carbon credits has a lot to say about the project's profitability. The future cost of the carbon credits is discussed more in chapter 6.1.

**Saved costs**

The star chart shows that the project is quite sensitive to changes in saved costs. An increase in the saved cost of 10 percent increases the NPV by 11 percent. The most significant uncertainty is whether waste incineration plants will be included in the EU ETS by 2030. It can have major consequences for the project if waste incineration is not included in the EU ETS. The future price of the $CO_2$ tax on waste incineration has just as much to say for profitability as the EU ETS. These are expected to complement each other. If the EU ETS prices go up, the $CO_2$ tax will be reduced. To simplify the analysis, it has been chosen to look only at how much impact the EU ETS has on the project's profitability, but the future costs for $CO_2$ tax have just as much to say.

**Share of biogenic emissions in the waste mix**

The star chart shows that the project is quite sensitive to changes in the waste mix and the share of biogenic emissions. An increase in the biogenic emission of 10 percent in the waste mix will reduce the NPV of 11 percent. It is initially difficult to calculate how much of the emissions are fossil and biogenic and how to decide what counts as what. This will never be entirely correct and is based mainly on the choice of method and calculations. In addition, it will always vary based on what kind of garbage comes in. The waste mix will never be exactly the same. The uncertainty surrounding these calculations makes it challenging to sell future credits in the VCM. This affects the expected revenue of the waste incineration plant.

**Discount rate**

As stated in the results, the actual return of capital is 11 percent and is high above the discount rate of 4 percent. This shows that the project can withstand a lot of risks. The choice of discount rate naturally impacts the project's profitability, but as it appears in the star chart, it is the variable that has the least impact on profitability. An increase in the discount rate of 10 percent reduces the NPV by 4 percent.

#### 5.2.3.2 Scenario analysis

The different scenarios are set up based on which correlations between variables are most likely. All scenarios are considered probable. The starting point for the scenarios and the assumptions are the same as the base scenario. No changes have been made if the assumption is not mentioned in the scenario description. The selected variables changed in each scenario and described. The scenarios are compiled according to insights gained in the market analysis.

**Scenario 1: There is no VCM**

This scenario shows the worst-case scenario for the VCM. It will not be possible for the waste incineration plant to receive any income from the CCS of the biogenic emissions. The income from carbon credit is therefore set to 0. The great uncertainty in the expectations of prices in the VCM makes it interesting to see how this affects the profitability of the waste incineration plant. This scenario is based on whether the EU ETS can lead to the plant's profitability withstanding that there will be no VCM. Table 14 shows how this will affect the NPV and the IRR.

*Table 14: Profitability assessment: scenario 1*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | 240 MNOK |
| **IRR** | 3,94 % |

This scenario gives a positive NPV of 240 MNOK. This indicates that the project still is considered profitable even without the income from the VCM. The IRR is 3,94 percent and above the discount rate.

**Scenario 2: Waste incineration is not included in the EU ETS**

It has not been finally decided in the EU that waste incineration will be included in the EU ETS. This scenario looks at the profitability if the plant does not achieve saved costs from the EU ETS. The saved cost from the EU ETS is equal to 0. Table 15 shows how this will affect the NPV and the IRR.

*Table 15: Profitability assessment: scenario 2*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | -68 MNOK |
| **IRR** | 1,4 % |

This scenario gives a negative NPV of -68 MNOK, and the IRR of 1,4 percent is lower than the discount rate. This indicates that the project is no longer considered profitable. The prices in the VCM are not high enough, and CCS will be considered unprofitable if waste incineration is not included in the EU ETS.

**Scenario 3: Higher costs of CCS**

The cost estimates are uncertain, and a scenario has been created based on increased costs for CCS. In this scenario, the increased cost are based on the highest estimate in the cost estimate illustrated in chapter 5.2.1.2 and Figure 16. This includes increased cost in investment costs, operation and maintenance costs and annual costs. The new cost estimates are shown in more detail in appendix B.

With the increased cost for CCS, the prices in the VCM will likely be driven up. This is based on the importance of additionality in the market. It is unlikely that the increased costs will only occur for CCS at waste incineration plants, it will apply to most projects with engineered solutions in the market. This will increase the prices of the credits in the VCM originating from engineered solutions. The price of a carbon credit is therefore set equal to the EU ETS scenario from the analysis of the VCM. This indicates a price of 1 475 NOK/t$CO_2$.

However, the same effect does not apply to prices in the EU ETS, as this price is set based on the cheapest measure to cut emissions in the market. The price in the EU ETS can be low compared to the VCM and the cost of CCS. In this scenario, the price is set equal to the lowest scenario from the market analysis of the EU ETS. The saved costs for the EU ETS will be 948 NOK/t$CO_2$. Table 16 shows how this will affect the NPV and the IRR.

*Table 16: Profitability assessment: scenario 3*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | 699 MNOK |
| **IRR** | 5,89 % |

With higher cost estimates and higher revenue from the VCM, the project achieves a positive NPV of 699 MNOK and an IRR of 5,89 percent. The project is considered profitable.

**Scenario 4: The VCM is a homogeneous market, and waste incineration is not included in the EU ETS**

As analyzed in the market analysis, it is expected that there will be a heterogeneous market with different prices for nature-based and engineered solutions. This scenario examines what happens if the market becomes homogeneous and it is a standard price for nature-based and engineered solutions. Assuming this, the price is set equal to the cheapest solution in the market. Therefore, the price for carbon credit is set equal to the lowest price scenario from the analysis of the VCM. The price of a carbon credit will be 300 NOK/t$CO_2$. In this scenario, waste incineration is not included in the EU ETS, and the saved costs from the EU ETS are set to 0. Table 17 shows how this will affect the NPV and the IRR.

*Table 17: Profitability assessment: scenario 4*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | -803 MNOK |
| **IRR** | -8,4 % |

The low prices in the VCM and the fact that the EU ETS is not included lead to a negative NPV of -803 MNOK and a negative IRR of -8,4 percent. This scenario results in a project that is not considered profitable.

**Scenario 5: The VCM is a heterogeneous market, and waste incineration are not included in the EU ETS**

This scenario is like scenario 4, but the prices in the VCM are set equal to the highest scenario from the market analysis. In this scenario, there is a heterogeneous market, and there are different prices for carbon credits originating from natural or engineered solutions. The carbon credits price is therefore set to 1999 NOK/tCO$_2$. Table 18 shows how this will affect the NPV and the IRR.

*Table 18: Profitability assessment: scenario 5*

| Profitability Assessment | **Value** |
|---|---|
| **NPV** | 1121 MNOK |
| **IRR** | 9,84 % |

Increased prices and a heterogeneous market in the VCM lead to a positive NPV of 1 121 MNOK and an IRR of 9,84 percent. Higher prices in the VCM make the project profitable without the saved cost from the EU ETS.

**Scenario 6: Lower costs of CCS and waste incineration is not included in the EU ETS**

The uncertainty associated with the cost estimates also means that the costs may be lower than in the base scenario. The costs in this scenario are based on the lowest estimate in the cost estimate illustrated in chapter 5.2.1.2 and Figure 16. The cost reduction applies to the investment costs, operation and maintenance costs, and annual costs. The estimated costs used in this scenario are shown more in detail in appendix C.

The EU ETS does not include waste incineration plants in this scenario. As estimated in scenario 3, where the CCS has a higher cost, carbon credit prices may be affected by the cost of CCS. The carbon credits will be priced lower because the costs of CCS are lower. Therefore, carbon credit will be equal to the lowest price scenario from the market analysis. The carbon credits will have a price of 300 NOK/tCO$_2$. Table 19 shows how this will affect the NPV and the IRR.

*Table 19: Profitability assessment: scenario 6*

| Profitability Assessment | Value |
|---|---|
| **NPV** | 336 MNOK |
| **IRR** | 6,12 % |

The scenario gives a positive NPV of 336 MNOK and an IRR of 6,12 percent. This scenario indicates that the lowest price in the VCM is enough to cover the lowest cost scenario of CCS at the plant. This even without the saved costs from the EU ETS.

### Compilation of the scenarios

Figure 19 summarizes and compares the NPV from the different scenarios. This indicates how much the NPV varies based on the type of scenario.

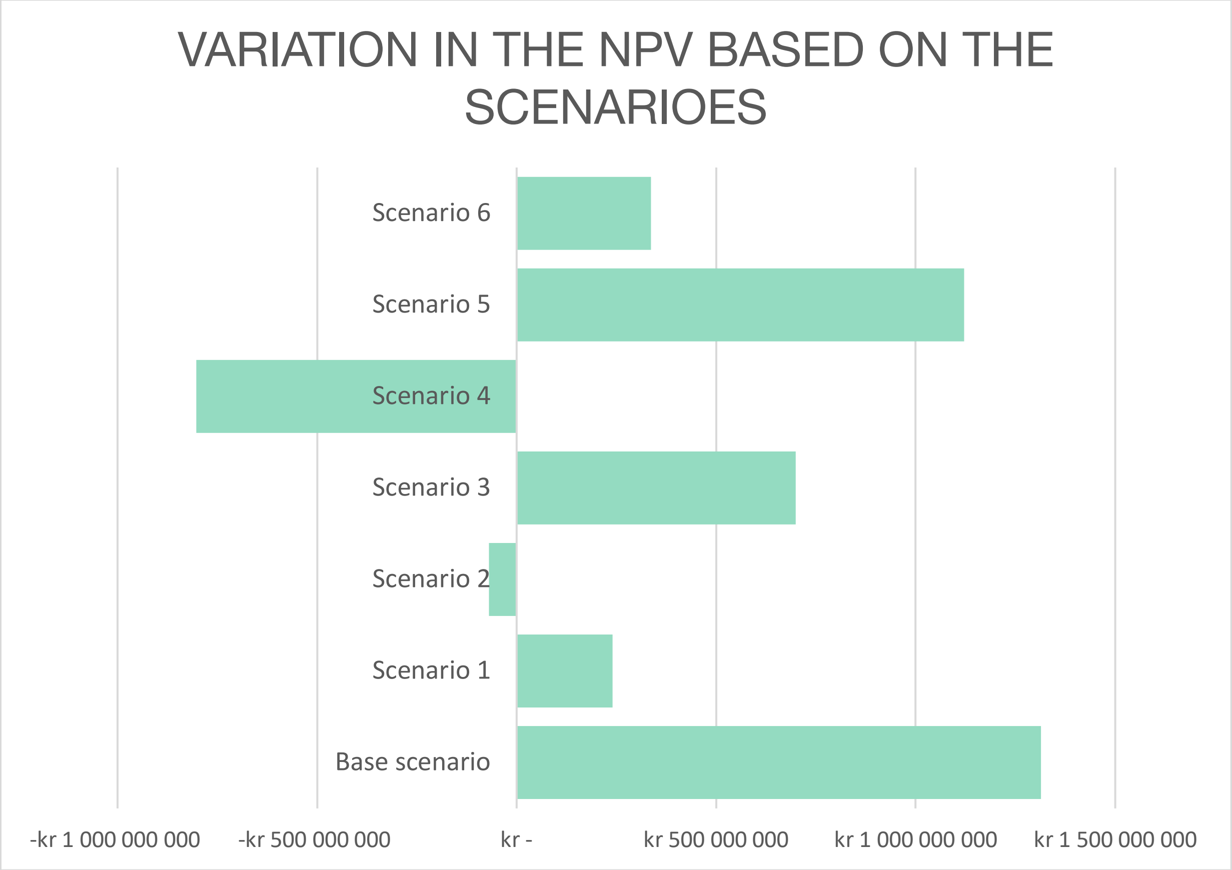


*Figure 19: Variation in the NPV based on the scenarios*

# 6 Discussion of results

Based on the results presented in chapter 5, this chapter aims to answer the main research question and the sub-questions. Since the thesis is divided into two parts, one market analysis and one profitability assessment, the discussion is divided similarly.

## 6.1 The market analysis

In this section, the purpose is to discuss the results from the market analysis of the VCM with a focus on the first sub-question:

1. *How will the voluntary carbon market and the prices and quantities of the carbon credits traded there develop towards and after 2030?*

I find that there is a clear expectation that both the prices and the quantitates of carbon credits traded in the VCM will increase. However, the prices of carbon credits are uncertain, and I presented five different price scenarios in chapter 5.1.1.10 of the VCM. Below I discuss the factors in the VCM leading to the expected price scenarios and the drivers in the market.

**Political drivers in the VCM**

The growing commitment from researchers and the UN's Climate Panel about the importance of creating negative emissions to reach the 1.5-degree target creates an increasing focus on capturing biogenic emissions. This increasing focus both nationally and internationally will make the need for a well-functioning VCM even more important. This can lead the VCM to develop in the right direction even faster.

**Price drivers in the VCM**

The mapped price drivers - methods, additionality, co-benefits, duration, and risk of premature release – are expected to affect the price in the future, reflecting increased emphasis on environmental policy in the years ahead. This is reflected in increased requirements from the authorities, the consumers, and the EU.

The vintage of the credit will become even more critical in the VCM as the market is constantly moving and growing. I think older credits will disappear from the market. It will be more important for companies to buy fresh credits. Credits put on the market years ago will not have the same standard or quality as the newer ones. I think this will eventually lead to the market being directed towards only selling credits the same year as they occur or before the capture occurs. A VCM with carbon credits within the same standard and verification will be priced higher.

Documentation and verification standards have a lot to say about how the market will develop towards 2030. The question is whether there will be a standard standardization and verification or if this will continue as it does today. For the carbon credit prices to be as high or higher than the EU ETS, I think the VCM must be able to guarantee that all credits sold in the market follow the same certifications and rules. They must at least be able to document for the same quality.

### Future Demand in the VCM

I find that the market has increased regularly from 2018 to 2022. The annual percentage increase from 2020 to 2021 was approximately 44 percent. This yearly percentage increase makes me believe that demand in the market will be higher than what was estimated by Trove Research. They expected a volume of 340-510 $MtCO_2e$ in 2030 (Trove Research et al., 2021), which means a maximal increase of 148-272 percent from the 2021-level distributed over nine years. The significant increase has been happening for just four years, and it is no guarantee that the growth will continue at the same speed towards and after 2030. There has been a clear dip in the market in the past, and it is not unnatural to expect this to happen again.

Based on the historical development in the market, I consider the estimates from Shell with an interval of 0,7-2 $GtCO_2$ yearly as most likely. Given the changes after COP26, the global market scenario seems particularly likely to happen. This means an expected volume of 2 $GtCO_2$ yearly (Shell & BCG, 2021). The estimates from TSVCM and McKinsey indicate a volume with an interval of 1,5-2 $GtCO_2$ yearly and reinforce this expectation (Blaufelder et al., 2021; TSVCM, 2021).

### A homogeneous or heterogeneous VCM

Historically, there has been a price variation based on whether it is a removal or a reduction project. In the future, I think there will probably also be a clear distinction between natural-based and engineered solutions. Whether it will be a homogeneous or heterogeneous market towards 2030 is considered decisive for how high the carbon prices can be set in the VCM. It is difficult to drive up the prices in a homogeneous market with cheap alternatives such as natural solutions. The prices in the VCM will most likely be determined by the cheapest option and remain very low as they are today. This means that engineered solutions must find another form of investment support and may disappear from the VCM. The market may be associated with greenwashing if this happens. Eventually, this may lead to the end of the VCM.

On the other hand, in a heterogeneous market, it will be possible to separate high-cost projects from low-cost projects. The high focus on additionality makes this scenario most likely. An engineered project will not achieve the requirement of additionality if the prices are set equal to the lowest nature-based prices. A heterogeneous market is also essential for achieving desired negative emissions. The rewarding of projects that can guarantee environmental benefits is important, and I think this priority will become more and more important.

**Extreme price scenarios**

There is a possibility, indeed a very low, that the VCM will disappear entirely and that the carbon prices will be equal to 0. It can be challenging to achieve a well-functioning VCM if the market's integrity does not improve and the market is associated with greenwashing. It is nevertheless important to point out that the probability seems minor. As the results show, many companies have a goal of becoming net-zero emitters. To achieve this, they must buy carbon credits, because it is impossible or costly to cut all the emissions throughout the whole value chain of the company. I therefore believe that the companies will choose to be more open and transparent about which credits they have bought and at what price. The desire in the EU to promote creating negative emissions strengthens the expectation that there will be incentives for CCS of biogenic emissions. It is difficult to estimate whether it will be in the form of a regulated or a voluntary market. This and the expected link between the EU ETS and the VCM have been discussed more in detail in chapter 5.1.1.8.

On the opposite end, it is also possible that the prices in the VCM will be higher than the prices in the EU ETS. The companies' desire to become net-zero can increase the willingness to pay for credit in the VCM rather than in the EU ETS. Increased willingness to pay therefore leads to increased prices in the highest scenario. This estimate, on the other hand, seems a bit high. This requires a very steep increase in price going forward.

## 6.2 Limitations of the study

The structure of the VCM turns out to be very different from the EU ETS. This means that I am uncertain about whether these markets will become more similar in the future. In the results chapter, I have assumed that the VCM and the EU ETS are two separate markets and that the biogenic emissions are not a part of the EU ETS. Nord Energi, which is the joint collaboration between the Nordic association for electricity producers, suppliers, and distributors, mentions in their consultation input to the new legislative proposal from the EU (European Commission, 2021b; Nordenergi, 2022) that there should be increased incentives to create negative emissions from engineered CCS on biogenic emissions. This may indicate more significant pressure on the EU to implement the biogenic emissions and the VCM to a greater extent by the EU ETS (Nordenergi, 2022). The prices of carbon credits will most likely be affected if this is the outcome.

The fact that the VCM is regulated by several industry-created standards leads to a large variation in the corresponding credit prices. If the EU ETS decides to include biogenic emissions in its market, the VCM will look different, and the prices may become more stable and predictable. This is because a joint body then regulates prices. The proposal from Nordenergi only involves including engineered solutions in the EU ETS, such as CCS at waste incineration. The engineered solutions will then disappear completely from the VCM, and it will cover only carbon credits that originate from nature-based solutions. The market will then be homogeneous, and it will most likely lead to lower carbon credit prices, as discussed in Chapter 5.1. I believe that this outcome does not have much to say for waste incineration plants. It is irrelevant whether the incentive for capturing the biogenic emissions comes from the VCM or the EU ETS. Therefore, this scenario is not included in the market analysis, but for a complete analysis of the VCM, this should have been carried out.

It is difficult to predict what the VCM will look like in the future as there are a lot of unforeseen events that can occur. There will always be major uncertainties associated with market analyzes of the future. Complete market analysis in such a secretive market has been demanding, and many uncertainties can pull the market in one direction.

## 6.3 Results from the Profitability assessment

In this section, the purpose is to discuss the results of the profitability assessment with a focus on the second research question:

2. *Will it be profitable for a waste incineration plant to invest in carbon capture and storage based on income from carbon credits origin from capturing the biogenic emissions?*

The result of the profitability assessment of the base scenario indicates that it is profitable to invest in CCS projects for waste incineration plants. In this chapter, I discuss results from the scenario analyses and how the results from the market analysis affect the profitability of CCS at waste incineration plants.

### LCOC

The base scenario resulted in an LCOC of 1 750 NOK/t$CO_2$. This estimate is in the interval of the estimated Levelized costs of 715-2716 NOK/t$CO_2$ found in the literature review in chapter 2.2. A major uncertainty associated with comparing the results from the literature and the result from this analysis is the size of the plant. The facilities described in the literature are at least four times larger. This can affect the costs in one direction or another. The wide estimate can have a major impact on the costs of the plant. The uncertainties regarding the costs are mentioned in chapter 5.2.1.4 and 5.2.1.5. What is clear from the result of the LCOC is that CCS at a waste incineration plant needs incentives to cover this cost, which does not exist today. The $CO_2$ tax of 1000 NOK indicates that the price of the incentive needs to be at least 750 NOK to cover the LCOC.

### Scenario analyses

Figure 16 in chapter 5.2.3.2 gives a picture of which scenarios have the most significant impact on the project's profitability. The main findings and the expected effects from the scenario analysis will be discussed further in the discussion chapter.

### The effect of no VCM

I found it interesting to analyze how the profitability of CCS at a waste incineration plant is affected by the fact that there will be no VCM in 2030. The result of scenario 1 shows that the project will be profitable even in a situation without income from the VCM. The NPV is significantly lower than the base scenario, but the project is still considered profitable. This may indicate that CCS at waste incineration is not necessarily so dependent on receiving income from the biogenic emissions to ensure profitability.

### The effect of waste incineration not included in the EU ETS

What is interesting is that without waste incineration being included in the EU ETS, the project is no longer considered profitable. It may seem that the project is dependent on the saved costs from the EU ETS. In the base scenario, the EU ETS price is set higher than the carbon credit price, which explains why the project is considered profitable with only the EU ETS but not carbon credits. It is nevertheless important to point out that the price difference between the EU ETS and the carbon credit is only 52 NOK. This indicates that the project is relatively seedless without income from the VCM or saved costs from the EU ETS. This confirms the findings in the literature review saying that CCS at waste incineration plants is not profitable without good enough subsidies or tax schemes.

These findings may indicate that the credit rates are set too low in the base scenario. Further analysis shows that the price of a carbon credit must be 1009 NOK for the project to be profitable without the EU ETS. Based on the market analysis, this is not an unlikely price to expect in the VCM by 2030. The results show that if the prices in the VCM are set a bit higher than the EU ETS, CCS at waste incineration will be profitable even without them being included in the EU ETS.

### The effect of the waste mix

The result of scenarios 1 and 2 are probably also a result of the amount of biogenic waste in the waste mix. The share of biogenic emissions is considered to be smaller than the fossil in 2022. A large share of biogenic emissions will mean that the prices in the VCM will affect the profitability of the project to a great extent. As shown in the result, the NPV will increase by 11 percent if the share of biogenic emissions increase by 10 percent. If the carbon credit price additionally increases from the base scenario, this will lead to an even higher NPV. It is important to add that this similarly affects the NPV negatively if credit prices fall. This shows that the share of biogenic emissions in the waste mix has a lot to say about how much impact the VCM has on the project's profitability.

### The effect of additionality in the project

In scenario 2 the credit price in the VCM is not set high enough to create profitability in the project. This means that the project is not additional and does not satisfy the requirements of the VCM. The requirement for additionality is a way of ensuring profitability in projects that create negative emissions. This means, in theory, that the carbon credits cannot be sold for the low price as in scenario 2. However, the companies' willingness to pay must be high enough for the credits to be sold. The danger is that the project will not be able to sell any credits on the VCM. Firstly, the project does not meet the requirement for additionality if the price is set at 948 NOK/t$CO_2$ and the credit quality is considered low. Secondly, if the credit price is set higher to achieve additionality, companies can choose cheaper projects that meet the requirement at a lower price.

### The effects of a homogeneous or a heterogenous VCM

The results of scenarios 4 and 5 indicate that it is critical for the profitability of CCS at waste incineration plants that the prices in the VCM become heterogeneous. This becomes especially clear when waste incineration is excluded from the EU ETS. In scenario 4 where there is assumed that the VCM becomes a homogeneous market, the project gets a clearly negative NPV. Especially in comparison with scenario 5, I see the effect of the two possible outcomes in the market. Scenario 5 has the same assumptions, but the low credit price is replaced with the highest expected price in the VCM. This, however, leads to a very positive NPV. This connection is clearly seen in Figure 19 in chapter 5.2.3.2. The findings from the market analysis prove to be correct and that it is crucial with the distribution between nature-based and engineered solutions.

**The effects of the cost estimates**

The result from the scenario analysis indicates that the costs do not affect the profitability to a very great extent. Scenario 6, however, shows how low costs for CCS lead to lower prices for the carbon credits. The NPV is lower than in the other scenarios. At the same time, scenario 3 shows that increased costs result in higher revenues from the VCM. It is important to establish this connection between the costs of the CCS, and the price excepted received in the VCM. This connection is not as evident in the EU ETS market. In the VCM, prices are, to a greater extent, adjusted according to the actual carbon capture project, but in the EU ETS, the prices are set according to the cheapest emission reduction technology. VCM can have a greater impact on whether CCS will become profitable at waste incineration plants.

## 6.4 Limitations of the study

To get a complete analysis of the investing of CCS at a waste incineration plant, the entire waste incineration plant calculations should be included. This is partly because it is expected that waste incineration can achieve a higher price for delivered waste because of being able to market for climate-neutral waste management. Increased focus on being net-zero in the entire value chain can lead to increased willingness to pay customers of the waste facility.

Estimating the distribution between the investment cost and the annual operation and maintenance costs is taken from a larger plant. The facilities from the Gassnova reports are on a much larger scale and are expected to capture approximately 400 000 tons of $CO_2$ annually. There is a risk that the distribution between investment and annual costs will not give a complete precis result for a plant estimated to capture 100 000 tons of $CO_2$ annually. Due to a lot of secrecy in the industry, this also applies to the cost of estimates used in the analysis.

Uncertainties about waste incineration becoming part of the EU ETS should have been addressed to a greater extent in the sensitivity analysis. The saved costs from the EU ETS contribute to high annual revenues in the cash flow. This is risky if it turns out that waste incineration will not be included in the EU ETS by 2030. The probability of it being introduced is expected to be high, but it is a factor that should have been analyzed more in detail.

In the cash flow analysis, I assume that the annual cost including the operation and maintenance costs are constant over the entire analysis period. This assumption is a simplification of reality. The yearly costs can both increase and decrease over the lifetime. They can increase as older equipment often requires more maintenance, or they can decrease because the more workers learn, the faster the work goes.

A weakness in the NPV calculation is that it does not consider that the agreements related to the carbon credits usually last for 5-10 years. By this, I mean that the buyers of the credits buy captured and stored emissions for a given period to a given price. In this thesis, this is simplified with an expected annual increase in the price when the income will, in reality, vary more periodically. Another weakness in the yearly increase percentage in prices may prove the opposite. As the cost of CCS at waste incineration plants decreases, so will the carbon credit price.

## 6.5 Discussion of the main research question

To summarize and discuss the main finding in the results, the main research question is discussed in this subchapter:

- *Can income from the sale of voluntary carbon credits for biogenic emissions ensure profitability in the investment of carbon capture and storage projects at waste incineration plants?*

The expected revenues from the VCM and the saved cost seem to have the most to say for the project's profitability. It may seem that the saved costs from the EU ETS, in combination with the $CO_2$ tax may be enough to cover the project's cost. The uncertainty associated with whether the waste industry will be included in the EU ETS by 2030 is great and it seems like a safer source of income to rely on carbon credits. The sale of carbon credits can make investing in CCS at waste incineration plants profitable given that prices are set high enough in the VCM by 2030.

Therefore, the development of the VCM has a lot to say about whether the sale of carbon credits can lead to profitability in CCS projects. For a well-functioning VCM, integrity must be ensured in the marked. I think the most important factors in achieving this are: a heterogeneous market, avoiding double-counting, additionality, and a standard for verification. At the same time, both large enough supply and demand must be in place so that the market has time to grow until 2030. If the market develops in this direction, the income from the sale of carbon credits can likely cover the cost of CCS at waste incineration plants. The mentioned factors affect each other to such an extent that if one does not happen, it will affect the entire VCM, and the market will function poorly. I then think it is difficult for the prices in the VCM to be high enough to cover the costs of CCS at a waste incineration plant.

# 7 Conclusion and further research

This thesis has aimed to examine whether the sale of carbon credits from biogenic emissions can ensure profitability in CCS projects at waste incineration plants. The market analysis of the VCM resulted in an expectation of the market size and different price scenarios towards and after 2030. Results from the market analysis used in the profitability assessment imply that the sale of carbon credits can ensure profitability in CCS projects at waste incineration plants. Further findings, however, show that several factors can affect this outcome.

The main findings in the market analysis indicate that the VCM will grow in the years towards and after 2030, both in quantitates and prices. This is, nevertheless, if the VCM overcomes some hurdles in the following years. Different price scenarios for carbon credits in 2030 were mapped based on findings in the market analysis. The great variety in the scenarios shows major effects based on how the VCM develops. It may also seem that the EU ETS will affect the VCM more than it has previously done.

The result from the profitability assessment shows that the sale of voluntary carbon credits from the biogenic emissions can lead to profitability in investing in CCS at waste incineration plants. This requires that the prices in the VCM are set high enough, or that waste incineration is included in the EU ETS. I observe that the project of CCS at waste incineration is most sensitive to changes in operation and maintenance costs, saved costs, carbon credit prices and the share of biogenic emissions in the waste mix. In particular, the future waste mix and how this is measured will have a lot to say for the project's profitability. The sensitivity analyzes indicate that the project is quite robust to changes. Although some uncertainties are associated with the analysis, the thesis is assumed to be robust enough to indicate that it will be profitable to invest in CCS at waste incineration plants by 2030.

The thesis addresses whether the incentive of selling carbon credits on the VCM is large enough to motivate the capture of biogenic emissions. So, it seems. Although only waste incineration plants have been analyzed in this thesis, the result will also apply to other plants with biogenic emissions. This is very positive regarding the need to create negative emissions to reach the target of 1,5 degrees. The result of this thesis should send a signal to private actors and companies in the waste industry. At the same time, a signal must be sent to politicians about the importance of incentivizing the capture of biogenic emissions and not just the fossil. The thesis also shows the importance of making the VCM more well-functioning and cohesive.

## 7.1 Future research

Considering the mentioned limitations of the study, several interesting areas have emerged that should be the subject of future research. The first thing I noticed that could have been interesting is to conduct a qualitative analysis like a survey or interviews. A lot of literature says something about how companies should think and act to achieve their goals, but there is little that says anything about what they are willing to do. Such a qualitative survey would also be interesting for all the market participants, project developers, brokers, retail traders, and end buyers. This would give a comprehensive impression of the expectations of the market.

It has been clear in the work of this thesis that there is an uncertainty associated with how to measure the amount of actual biogenic and fossil emissions from a waste incineration plant. The waste mix will change in the years ahead and, there must be precise methods for this. Reasonable and standardized solutions must be designed and mapped for this. It would have been interesting to examine how this should be done.

For further examination of the profitability of such projects, more details from the cost picture should be obtained. It would have been interesting to look at how profitability is affected by heat integration, choice of transport, distance to local port/final port, and size of the plant. The costs associated with CCS and how the cost picture develops over the lifetime need to be analyzed. Another exciting aspect is how CCS at waste incineration plants affects the revenues the plant can take for receiving waste. There are many exciting aspects related to the cost of CCS in waste incineration plants that should be investigated more closely.

Finally, I ask the question: can costs for all tons of carbon captured be compared regardless of the project? The answer is most likely no. Carbon Plan (2020) argues that the duration and risk of the emissions captured must be included in the calculations for the cost of carbon removal. This is especially true when calculating the carbon price difference of nature-based and engineered solutions. To calculate the costs between the nature-based projects, a risk-adjusted interest rate must be added to consider storage time and risk of premature release. Carbon Plan has therefore developed a model that consider this and calculates the cost of temporary carbon removal (Cullenward et al., 2020). With this as a method, it would have been interesting to see how this would affect estimated prices in the VCM and the distinction between nature-based and engineered-based solutions.

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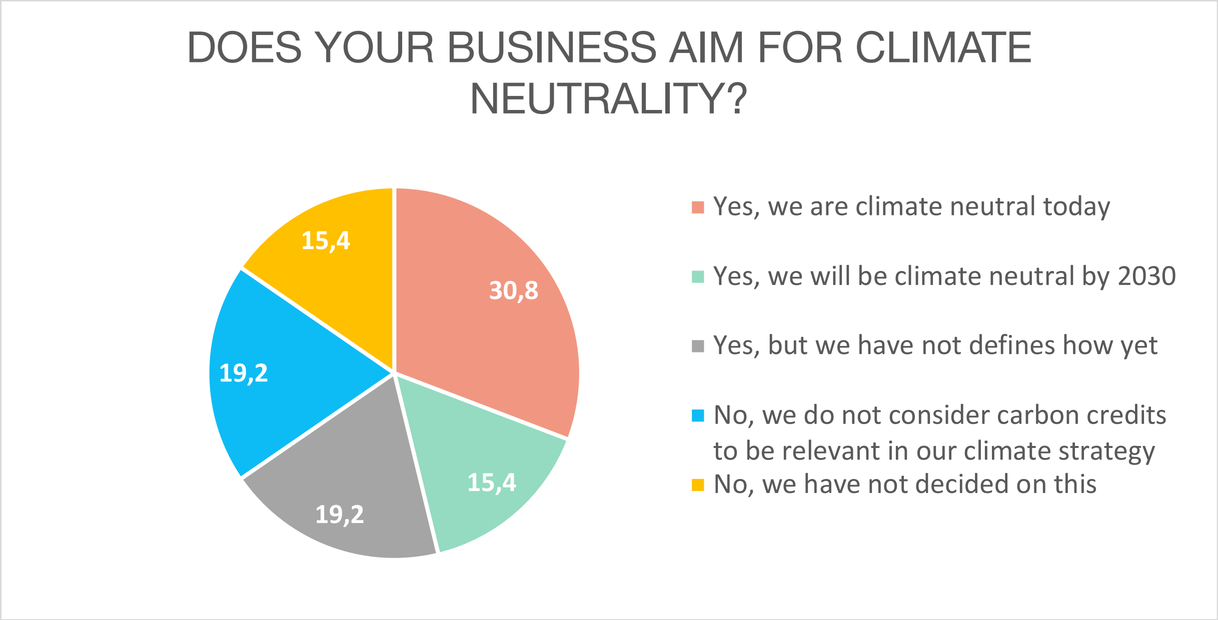
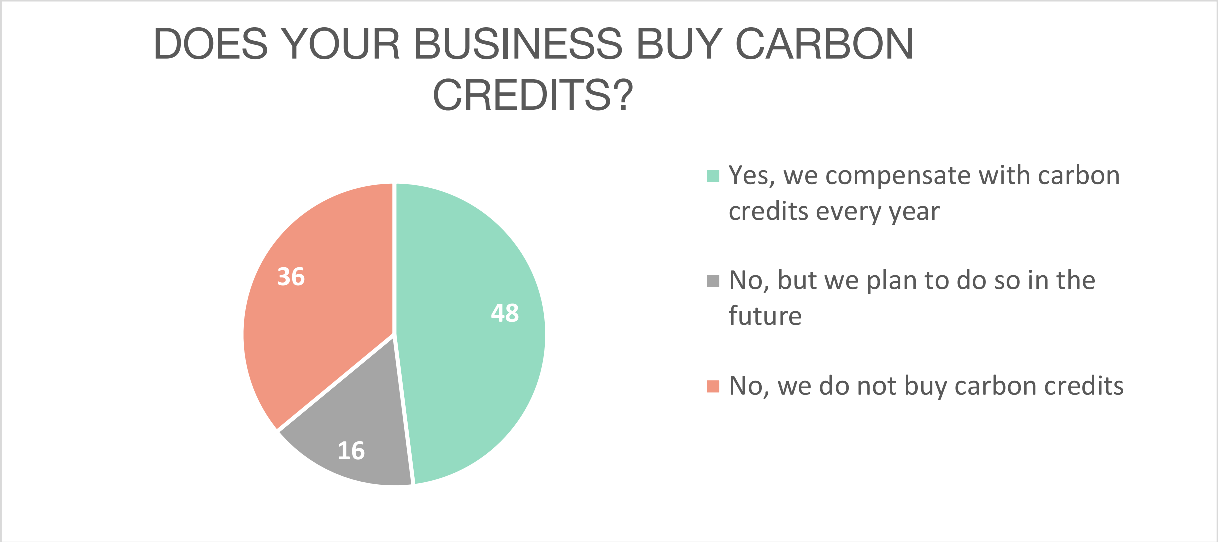
# 9 Appendix

## Appendix A: Survey





Survey conducted by PwC and Zero (2022)

## Appendix B: Cost estimates scenario 3

| **Investment Costs** | |
|---|---|
| **Capture and Liquidation** | 738 MNOK |
| **Local Transport and Intermediate Storage** | 308 MNOK |
| **Total Investment Cost** | 1046 MNOK |

| **Operation and Maintenance Costs** | |
|---|---|
| Capture and Liquidation | 41 MNOK/annually |
| Local Transport and Intermediate Storage | 17 MNOK/annually |
| Large-scale Transport and Storage | 80 MNOK/annually |
| **Total Annually and Operation and Maintenance Costs** | **138 MNOK/annually** |

## Appendix C: Cost estimates scenario 6

| Investment Costs | |
|---|---|
| **Capture and Liquidation** | 431 MNOK |
| **Local Transport and Intermediate Storage** | 62 MNOK |
| **Total Investment Cost** | 493 MNOK |

| Operation and Maintenance Costs | |
|---|---|
| Capture and Liquidation | 24 MNOK/annually |
| Local Transport and Intermediate Storage | 3,4 MNOK/annually |
| Large-scale Transport and Storage | 20 MNOK/annually |
| **Total Annually and Operation and Maintenance Costs** | **47,4 MNOK/annually** |

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