Handelshøyskolen BI

GRA 19703 Master Thesis

Thesis Master of Science 100% - W

Predefinert informasjon

Startdato:	09-01-2023 09:00 CET	**Termin:**	202310
Sluttdato:	03-07-2023 12:00 CEST	**Vurderingsform:**	Norsk 6-trinns skala (A-F)
Eksamensform:	T		
Flowkode:	202310||11184||IN00||W||T		
Intern sensor:	(Anonymisert)		

Deltaker

Navn:	Diu Thi Nguyen og Hau Hai Nguyen

Informasjon fra deltaker

Tittel *:	Supply chain network design for carbon capture, transportation and storage
Navn på veileder *:	Erna Engebrethsen

Inneholder besvarelsen konfidensielt materiale?:	Nei	**Kan besvarelsen offentliggjøres?:**	Ja

Gruppe

Gruppenavn:	(Anonymisert)
Gruppenummer:	285
Andre medlemmer i gruppen:	

Table of Content

Acknowledgements

This master thesis represents the completion of our Master of Science in Supply Chain and Operations Management degree at BI Norwegian Business School. Writing this thesis has been one of, if not the most, challenging tasks during our master's studies. The process of writing this paper has taken us on a rollercoaster of emotions: ranging from excitement to moments of anxiety, and even panic. However, ultimately, we are filled with happiness and satisfaction as we have completed this important project.

Above all, this work would not have been successfully completed without the significant support and contributions of many individuals. First and foremost, we want to express our gratitude to our supervisors at BI Norwegian Business School, Mehdi Sharifyazdi and Erna Engebrethsen, for their outstanding support and feedback. You have always responded to our inquiries and provided us with guidance, steering us in the right direction throughout the thesis writing process.

Secondly, a special gratitude we would like to say to Bahman Bohloli, Senior Specialist at NGI, who has been with us from the very beginning of this thesis. Your willingness to help, knowledge on the topic and swift and detailed responses have been instrumental in helping us overcome challenges and navigate through the thesis successfully.

Thirdly, we would also like to thank all participants in our project. Your invaluable contribution has played a crucial role in advancing our paper to its current state.

Finally, we would like to sincerely thank our families and friends for their constant encouragement and unwavering support throughout the entire journey of writing this thesis.

BI Norwegian Business School, July 2nd, 2023

Diu Thi Nguyen and Hau Hai Nguyen.

Abstract

Purpose – Climate change, mainly caused by greenhouse gas emissions (GHG), has become one of the most significant challenges facing humanity. Meanwhile, carbon dioxide (CO_2) emissions are recognized as the primary contributor to GHG. Therefore, reducing CO_2 emissions plays a pivotal role in addressing climate change and global warming. CO_2 capture, transportation and storage (CCS) emerges as a promising way to remove CO_2 emissions from the atmosphere, especially those emitted from hard-to-abate industries. Although CCS has gained significant attention in recent years, its implementation remains limited. Thus, the objective of this thesis is to explore the design of an economically effective large-scale CCS supply chain network at a national level while concurrently fulfilling different emissions reduction targets.

Methodology – A combination of model-based quantitative and qualitative methods with a case study design was employed. Both secondary data and primary data were collected and analyzed. A total of 9 interviews were conducted with experts in CCS and SCND for CCS.

Findings – By using a mixed integer linear programming and bi-objective optimization framework, minimum-cost supply chain networks are here designed to meet different CO_2 avoidance targets in Norway. The research identifies the twenty most significant CO_2 emitters in the land-based industry and includes them as potential candidates for capture. Techno-economic representations of capture units across various sectors and transport modes are incorporated. The results determine optimal supply chain configurations in terms of the selection and sizing of capture units, selection of transport modes among ship, truck and pipeline, and CO_2 transport routes.

As the target of CO_2 avoidance increases from 0.5 Mt/year to its maximum attainable value equivalent to 7.98 Mt/year, the resulting minimum cost for the network increases from 21.4 to 938.7 M€/year. On average, the capture cost constitutes the main part of the total cost at 52%, followed by the storage cost at 30% and the transport cost at 17%. Furthermore, it is suggested that a carbon tax should be set to be at least 75.3 €/tCO_2 for avoiding just above 50% of total current emissions from considered sources. Regarding the selection of CO_2 sources, four criteria are found to affect the optimal network, which are unitary capture cost, location, size of CO2 emissions, and capture efficiency.

The study also shows that the emissions of the system are consistently below 1% of the total CO_2 stored. Moreover, it emphasizes the dominance of the pipeline transport, but only for distances under 420km. In contrast, truck transport and ship transport present a minor role in the CCS transport network. Trucks are cost-optimal for only small amounts of CO_2 and short distances, while ships are applied only when higher carbon reduction targets require capturing CO_2 from more distant parts of the system.

Research Limitations – Firstly, this research faced limitations in obtaining responses from practitioners while attempting to collect data relevant to the Norwegian context. Secondly, time-dependent factors and uncertainties were not addressed in the model. Finally, the scale effects of the plant size on the capture cost and the distinction between onshore and offshore pipelines were not examined.

Keywords – SCND, CCS, CCS network, CCS supply chain network design, CO_2 capture, transport and storage.

List of Abbreviation

ASEAN: Association of Southeast Asian Nations

CA: Continuous approximation

CAC: Cost of avoided CO2

CCS: Carbon capture and storage

CCU: Carbon capture and utilization

CCUS: Carbon capture, utilization and storage

CEPCI: Chemical engineering plant cost index

CSC: Cost of stored CO2

CSRC: CO_2 Storage Resource Catalogue

EOR: Enhance oil recovery

ETS: Emissions Trading System

FMIP: Fuzzy mixed integer programming

FSI: Floating storage and injection

GHG: Greenhouse gas

GIS: Geographical information system

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

kt: kilotonnes

LNG: Liquefied natural gas

LP: Linear programming

LPG: Liquefied petroleum gas

MILP: Mixed integer linear programming

MINLP: Mixed integer nonlinear programming

MINP: Mixed integer nonlinear programming

MIP: Mixed integer programming

MOO: Multi-objective optimization

Mt: megatonnes

NGI: Norwegian Geotechnical Institute

O&M: Operation and maintenance

R&D: Research and development

SCND: Supply chain network design

SMIP: Stochastic mixed integer programming

SOEs: State Owned Enterprises

TC: Total cost

TCC: Total capture cost

TCM: Technology Centre of Mongstad

tCO_2: metric tonne of CO_2

TSC: Total storage cost

TTC: Total transport cost

ZEP: Zero Emission Platform

List of Figures

List of Tables

1. Introduction

1.1. Background

1.1.1. Greenhouse gas and climate change

Anthropogenic greenhouse gas (GHG) emissions have been recognized as the main culprit of global warming and climate change. The greater GHG emissions, the more severe the warming and its associated consequences. These consequences comprise sea level rise and a higher incidence of extreme weather events such as destructive storms, heat waves, bushfires, droughts and floods, which in turn pose a dire threat to food production, human health and businesses worldwide (European Commission, n.d.-a). Assessment of observed changes at a global scale demonstrates that there is a discernible impact of human-caused climate change on many physical and biological systems on all continents and in most oceans (Rosenzweig et al., 2007).

The emissions of GHG are mainly composed of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases, of which CO_2 is the most abundant and accounts for about 76 percent (Center for Climate and Energy Solutions, n.d.). Global CO_2 emissions have experienced an exponential increase since pre-industrial period, causing acceleration of global warming. More specifically, CO_2 emissions rose slowly from 2 Gt/year in 1850 to about 5 Gt/year in the mid-20th century before skyrocketing to over 35 Gt/year in 2022 (NOAA, 2023b). The annual report from NOAA's Global Monitoring Lab indicates that despite pandemic dip, the global average atmospheric CO_2 set a new record high in 2022: 417.06 parts per million (ppm), 50% higher than pre-industrial levels (NOAA, 2023a). To mitigate global temperature change, huge efforts are therefore needed to limit the concentration of CO_2 in the atmosphere.

The impact of GHG on the climate already raised some concerns in 1988 with the establishment of The Intergovernmental Panel on Climate Change (IPCC) (IPCC, n.d.), but only after the Kyoto Protocol's foundation in 1997 with the participation of 192 Parties was the first treat for reduction of GHG emissions conducted (IEA, 2016). This laid a basis for the Paris Agreement - the first universal and legally binding treaty on climate change to be adopted in 2015. Accordingly, 196 Parties agreed in keeping the global average temperature increase to well below 2°C compared to pre-industrial levels and pursuing efforts to limit the increase to 1.5°C by 2050 so that the climate-related impacts and risks for natural and human systems are minimized (UNFCCC, n.d.; IPCC, 2018). Pathways achieving this aim require a substantial reduction in CO_2 emissions in all sectors, especially in energy and industry, given that they are responsible for about 60% of total anthropogenic CO_2 emissions worldwide (United Nations, 2015; IEA, 2020). In Europe, power generation, iron and steel production, cement production and oil refining currently contribute to the biggest quotas of CO_2 emissions from stationary sources (d'Amore et al., 2021a).

1.1.2. Mitigation options and CCS

In 2005, the EU Emissions Trading System (ETS) was launched, allowing power and industrial plants to trade their GHG emission allowances. This scheme sets a cap on and gives a price to CO_2 emissions, thereby incentivizing the industries to diminish their emissions (European Commission, n.d.-b). Various strategies for CO_2 reduction while meeting growing energy demand have been proposed and applied, which include employing geoengineering approaches such as afforestation and reforestation (Leung et al., 2014), enhancing plant efficiency through utilizing more advanced technologies with the same fuel amount (IPCC, 2007), partly replacing existing fossil fuel power plants by nuclear power plants that consume much smaller quantities of fuels (IEA, 2006), using renewable energy sources to provide electricity (from hydro, solar, wind, bio-energy and geo-thermal generation) or heat (from solar, biomass or geo-thermal) (EEA, 2017), and applying carbon capture and storage (CCS) system.

Among above-mentioned options, CCS has received increasing attention particularly following the IPCC report in 2005 about this technology (IPCC, 2005). In more recent reports of IPCC, the potential of CCS in reducing CO_2 emissions has also been given credence to (IPCC, 2018). While it is technically feasible and expected to happen in the near future for the power sector to transition towards renewable or low carbon sources, CCS is considered as the only option to achieve a long-term and significant decarbonization of hard-to-abate industries such as cement, aluminium, iron and steel, refineries and chemicals manufacture (European Commission, 2020). As these industries have inherent CO_2 emissions coming from energy-intensive industry process itself, alternative mitigation options might be very expensive or never exist (Global CCS Institute, 2017). The fifth report of IPCC (2015) indicates that the global costs of keeping the temperature increase below

2°C could be more than twice as high without CCS. Besides, in such areas as Europe, technological upper limits have been reached regarding energy efficiency, making CCS even more important. When fully implemented, CCS might contribute to the reduction of at least 20% of global CO_2 emissions by 2050.

The general concept of CCS is to prevent CO_2 emissions generated from stationary sources from entering the atmosphere by storing it permanently underground. Particularly, CCS includes three echelons: capture, transportation and storage (IPCC, 2005). The first echelon involves separating CO_2 from other gases of a process stream. The second step is the transportation of the captured CO_2 via either pipeline, ship or road/rail towards a storage location. Finally, CO_2 will be injected into geological basins suitable for sequestration to be isolated from the atmosphere (Equinor, n.d.-a). CCS is not designed to avoid CO_2 emissions in the first place, but instead, it is designed to dispose of CO_2 produced by industrial process and power facilities. In theory, CO_2 should be reutilized in different processes rather than being stored underground. However, the utilization of CO_2 is currently limited in a few areas such as enhanced oil recovery (EOR) due to low-efficient and high-cost technologies. Thus, the utilization process will not be considered in this thesis.

CCS has been becoming increasingly competitive and commercial worldwide. The first carbon capture facility was proposed in 1938, then the first large-scale project with a view to injecting CO_2 underground was launched in Texas in 1972 (Anuradha Varanasi, 2019). 24 years later, Norway’s Sleipner became the world’s first offshore CCS project with the goal to reduce CO_2 emissions from natural gas processing industry (Equinor, 2022a). According to Global CCS Institute (2022), as of September 2022, there are 196 projects in the CCS facilities pipeline worldwide, in which 30 are in commercial operation, 11 are in construction, 153 are in different development stages and 2 are suspended. Compared to 2021, the number of CCS facilities witnessed an impressive increase of 44 percent.

In Norway, since the first successful CCS project, the Norwegian government, academia and industry have been continuing to develop CCS. The country has led the CCS transition in Europe by rolling out supportive policies that drive investment in CCS from industry (Global CCS Institute, 2023). In 2012, the world’s biggest test center for CO_2 capture, Technology Centre of Mongstad (TCM), owned by the Norwegian state, was inaugurated (CCS Norway, n.d.-a). In 2020, Norway launched the Longship project which is a full-scale CCS project demonstrating CO_2

capture from a cement factory and a waste incineration plant as well as CO_2 transport by ships and CO_2 storage in the Norwegian continental shelf (Norwegian Ministry of Petroleum and Energy, n.d.). This project has had a positive influence on the progress of CCS with active engagement of European industry in technology development.

Although full-scale CCS projects such as Longship are vital first steps to facilitate full employment of CCS in the future, they are single CCS chains. It is estimated that more than 2000 CCS facilities worldwide should be in operation by 2050 to meet the goals of the Paris Agreement (Global CCS Institute, 2020a). Thus, large-scale expansion of the single chain into a widespread and cost-effective network of different sources, transport means, and storage sites is required. For this purpose, the concept of optimal supply chain network design has emerged as a crucial research task (d'Amore et al., 2021a). Accordingly, quantitative modelling tools and typically mixed integer linear programming (MILP) have been recently used to design optimal CCS supply chain networks under technical and market constraints and enable their effective application at various scales.

This thesis's objective is to design an optimal CCS supply chain network at a country level considering the system cost and target about emissions reduction. Norway is chosen as the case study, and only CO_2 emissions from industrial domains are focused on given the important role of CCS in the decarbonization of these areas and the data availability. The thesis's findings can provide Norwegian government and industry a useful method to enable large-scale penetration of CCS infrastructures in the future.

1.2. Research question

Based on the background information and our interest in this topic, the research question is derived: **"How can the supply chain network for CO_2 capture, transportation and storage be designed to minimize total costs and meet the CO_2 avoidance targets?"**. This question has been chosen since we want to investigate an optimal network, in terms of economic and environmental perspective, for capture, transportation and storage of CO_2.

This research question will be answered through a case study in Norway, where we will assess the supply chain network for CO_2 retrieval, transportation, and storage: the locations at which CO_2 is produced, transportation modes that are being utilized to transport CO_2, and potential geological reservoirs and technology for CO_2 storage. The optimization results will give the best design configurations of CCS by determining the optimal location and sizing of capture plants across different sectors, the optimal transportation routes and means among ship, truck and pipeline and the sequestration sites to be selected as well as CO_2 amounts to be stored in each chosen site.

1.3. Relevance of the research

1.3.1. Theoretical relevance

Among many different ways to reduce CO_2 emissions, CCS offers the possibility to remove a huge amount of CO_2 emissions from the atmosphere (Global CCS Institute, 2019). According to CICERO (2019), CCS application is a prerequisite to meet the Paris Agreement target. In addition, the effectiveness of CCS projects depends significantly on the CCS supply chain network design. Hence, designing an optimal CCS supply chain network has become a research topic of the utmost urgency (Becattini et al., 2022; d’Amore et al., 2021a). However, while this topic has been examined in several papers from the technical perspective, there is still limited research from the business perspective.

Over the past decade, the research on end-to-end supply chain network of CCS system has been increasing along with the growing concerns about climate change. However, most of them pay attention to medium and large-scale emission sources and only focus on pipeline and/or ship as the potential transportation modes when designing a CCS network. Besides, they normally implemented mathematical programming models with only one economic objective such as minimization of the total system cost in case of CCS or maximization of the net revenue in case of carbon capture, transportation, and utilization (CCUS). Meanwhile, it is necessary to develop models with multi-objective optimization to investigate the impact of sustainability objective on the design of CCS supply chain network (Hasan et al., 2022). This is because the goals of minimizing the total cost and maximizing the amount of CO_2 avoided in CCS network are normally two conflict objectives: the more the CO_2 is avoided in CCS system, the higher the cost is and vice versa.

Moreover, to do this thesis, some of the most relevant research on supply chain network design for CCS has been reviewed. For example, considering pipeline and ship transport, d’Amore et al. (2021b) developed a model with the objective of minimizing total system cost for designing an optimal CCS supply chain from industrial sources, including steel, cement and refinery sectors at European level, or Becattini et al. (2022) presented an optimization model with multi-modal transport technologies, such as pipeline, ship, barge, rail and truck, for the optimal design of CCS supply chain from waste-to-energy sector in Switzerland. As a result, with the use of a case study in Norway, this study differentiates itself from existing research and is aimed to fill gaps in literature by (1) considering emissions sources from a variety of sectors (namely cement, iron and steel, refinery, petrochemical, aluminium, silicon, fertilizer and natural gas processing) and many different transport modes (i.e. pipeline, ship and truck) to provide a comprehensive model for designing an optimal CCS network; (2) using multi-objective model to optimize the economic and environmental objectives; (3) proposing a multi-echelon and multi-stage MILP model that exhibits flexibility and generalization so that the model can be adjusted to other context; (4) designing a CCS network at a nation-wide level to enable the investigation of the possibility to cluster small emission sources, which is in line with the suggestion about future work of d'Amore et al., (2021b).

1.3.2. Practical relevance

While CCS system plays a critical role in decarbonization, the progress of CCS deployment is relatively slow in comparation with the increased rate of global warming. This slow progress can partly be explained by techno-economic risks and uncertainties of CCS systems. Nonetheless, these risks and uncertainties can be mitigated by the availability of powerful decision support tools (Tapia et al., 2018). Thus, the more practical settings are studied in this area, the more valuable the academic contributions are. As a result, this thesis will be of practical relevance as it provides companies and authorities tools and methods to design an optimal supply chain network for CCS.

Additionally, this paper will be of practical relevance to Norwegian leaders since it presents a real-life situation and application in Norway. Norway's target is to become a net-zero emission society by 2050 (Norwegian Ministry of Climate and Environment, 2021) through reducing emissions by at least 50% and toward 55% by 2030 compared to the 1990 level. Besides, in Norway, a major amount of CO_2 is produced by industrial domains (Statistics Norway, 2022). Consequently, decarbonization of Norwegian industrial emission sources is crucial to help the country achieve its ambitious goal. Applying widespread CCS systems is believed as the unique way to remove CO_2 generated from industrial sectors in Norway.

However, there exists limited research on designing an optimal CCS supply chain network under Norwegian context. While Klokk et al. (2010) present a mathematical model to design a CO_2 value chain in Norway, it considers only pipeline transport and five CO_2 emissions sources. Also, their work was conducted a long time ago and thus has become less relevant to today's context. Hence, by considering a wider range of CO_2 sources in hard-to-abate industries and multi-modal transport network, this study will propose a new and more comprehensive model for optimizing CO_2 supply chain network at the nation-wide scale, helping Norwegian leaders make better decisions.

1.4. Structure of the thesis

This thesis is organized into six chapters. Following the introduction, chapter two presents a literature review that highlights previous theories and concepts relevant to the topic being studied. The next chapter outlines our research methodology to explain how we answer the research question and ensure the quality of the research. Chapter four elucidates the system configuration in Norway in terms of capture, transport and storage stages and provide the mathematical formulation of the optimization problem. All modelling inputs and assumptions are clearly indicated in this chapter. The optimization results and our analyses are then discussed in chapter five before we conclude the work with some final remarks and suggestions for future research.

2. Literature review

In this chapter, we will present an extensive review of the scientific studies pertaining to our research topic. To build a theoretical basis for our study, we have searched and investigated a combination of literature on CCS supply chain, supply chain network design (SCND) and SCND for CCS. Section 2.1 describes components of a CCS supply chain as well as challenges and opportunities of building and operating a CCS supply chain network. Section 2.2 gives an overview of SCND, and modelling methods used in extant literature to solve the supply chain optimization problem. Finally, section 2.3, which is the main part of this chapter, critically reviews literature in the field of SCND specifically for CCS. By doing so, we can gain insights into this research area and identify topics that are of theoretical and practical relevance for future research.

2.1. CCS supply chain

According to Bui et al. (2018), CCS implies a suite of technologies that allow CO_2 to be captured at stationary sources (i.e., industries or power plants), transported via ship, pipeline, truck or rail to the sequestration site and finally injected into subsurface reservoirs through wells. Thus, components of a CCS supply chain are capture, transportation and storage. Figure 2.1 depicts a schematic overview of the CCS chain where each component is essential to the technical and economic viability of the CCS system. The most common capture methods are post-combustion, pre-combustion and oxy-fuel combustion. When it comes to the geological CO_2 storage options, they include coal streams, salt domes, saline aquifers and active or depleted hydrocarbon fields (Raza et al., 2016).

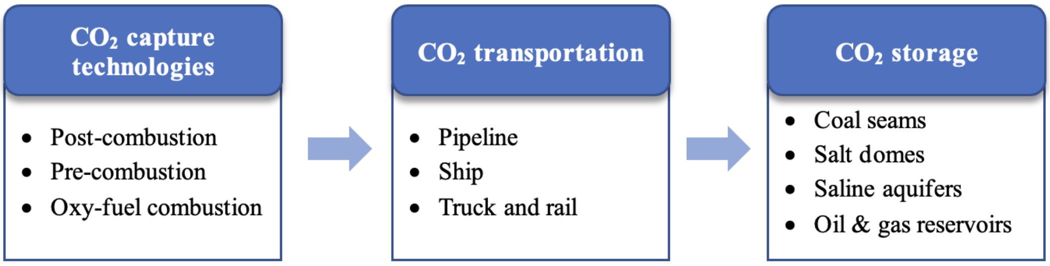


Figure 2.1. CCS supply chain *(synthesized by authors)*

2.1.1. Carbon dioxide capture

According to Omoregbe et al. (2020), little or no research on carbon capture was conducted until 2008 when legislative measures were introduced to abate climate change and industry awareness of the matter grew. To date, there have been more than 1000 publications including proceedings papers and articles related to carbon capture technologies with the involvement of over 50 countries and 200 journals. Regarding continents, Europe was the most productive, followed by Asia, based on the number of publications and citations.

The research trends in carbon capture are within three different technological concepts, namely post-combustion, pre-combustion and oxy-fuel combustion, in which post-combustion is the most referenced capture technology with more than 80 percent of publications. Meanwhile, only 3.4 percent of publications refer to oxy-fuel combustion capture technology until 2018 (Omoregbe et al., 2020; Osman et al., 2021). However, this technology has gained more attention from academia and industry in recent years (Yadav & Mondal, 2021).

2.1.1.1. Post-combustion

Post-combustion capture is the most popular solution for CO_2 capture. This technology involves capturing CO_2 from flue gases after the combustion process. Instead of being directly released into the air, the flue gases are passed through a system that separates the majority of the CO_2. A pure stream of CO_2 is then fed into a reservoir for storage while the remaining gases are discharged into the atmosphere. In the post-combustion-based technology, using a chemical sorbent is the leading method for CO_2 separation, among which, amine-based absorption is the most used technique with a capture efficiency of around 90 percent. Wilkes & Brown, 2022). The general overview of post-combustion capture is presented in Figure 2.2.

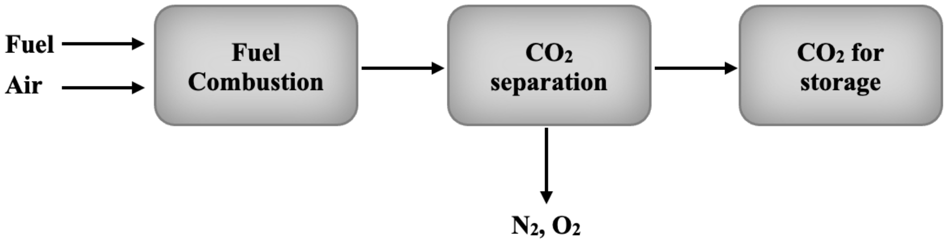


Figure 2.2. Post-combustion carbon capture *(synthesized by authors)*

The major benefit of post-combustion capture is that this technology can be retrofitted into most existing power and industrial plants without significant changes to the original facility (Herzog et al., 2009). It can also be utilized in new plants to achieve the targets about the reduction of GHG emissions (Zhao et al., 2016). Besides, post-combustion carbon capture, due to its maturity, offers a lower technology risk in comparison to other competing options. (Basile et al., 2011). However, this technology comes with several challenges such as low CO_2 concentrations and pressures in flue gas, which resultantly requires high energy amounts to be expended in the capture process (Leung et al., 2014; Wang & Song, 2020)

2.1.1.2. Pre-combustion

Pre-combustion capture involves removing CO_2 from the fossil fuel before the combustion process ends. Figure 2.3 shows the general schema of pre-combustion carbon capture technology. First, the fuel is reacted with oxygen or air and steam to produce synthesis gas (syngas) or gas composed of hydrogen and carbon monoxide. The carbon monoxide is subsequently reacted with steam to give CO_2 and more hydrogen. Then, CO_2 is separated, typically by a chemical or physical absorption process, leaving a hydrogen-rich fuel that can be utilized in many applications. The goal of the whole system is to convert the carbon fuel into carbonless fuel before it is burned and retrieve CO_2 for storage. Oil, coal, natural gas and biomass can be used for this technology. (Pires et al., 2011; Carpenter & Long, 2017)

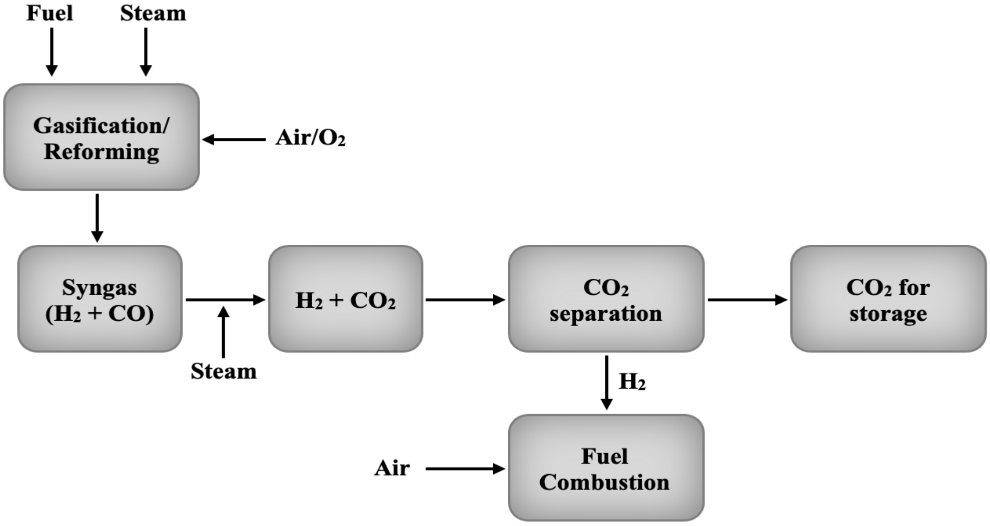


Figure 2.3. Pre-combustion carbon capture *(synthesized by authors)*

An important benefit of pre-combustion capture compared to post-combustion capture is higher CO_2 concentrations and pressures in the output stream. As a result, the energy demand for CO_2 retrieval is lower Elhenawy et al., 2020). However, due to the more complex installation of equipment, the investment costs for pre-combustion capture are higher. According to Tock & Maréchal (2013), the annual investment costs for both technologies are the same since the higher energy efficiency of pre-combustion capture offsets the additional investment.

2.1.1.3. Oxy-fuel combustion

Oxy-fuel combustion, as depicted in Figure 2.4, refers to the usage of nearly pure oxygen instead of air for combustion. Thus, the first step is to produce oxygen, usually by low temperature air separation. Subsequently, fossil fuel is burnt with pure oxygen, which gives the exhaust gas composed of only CO_2 and steam. Steam can easily be condensed into water, resulting in a pure CO_2 stream for storage. Yadav & Mondal, 2021)

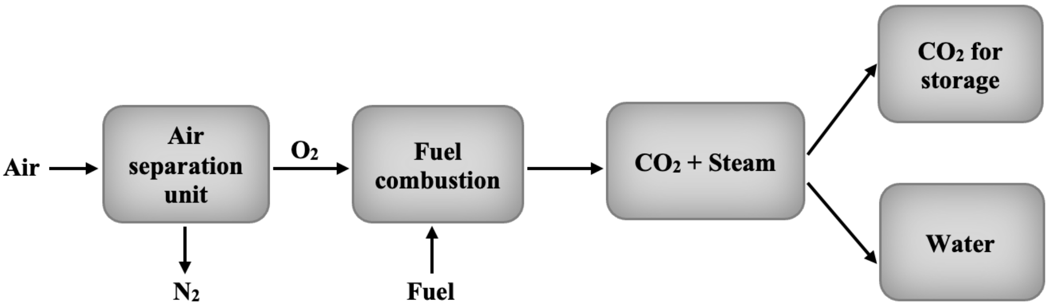


Figure 2.4. Oxy-fuel combustion carbon capture *(synthesized by authors)*

Oxy-fuel combustion capture rate is very high. In particular, it is possible to capture nearly 100 percent of the CO_2 using this approach while there are less emissions emitted to the atmosphere compared to air-fired combustion. However, it is found that the energy consumption of the system for oxy-fuel combustion is very intensive due to the use of air separation unit to produce oxygen. This is the bottleneck limiting further commercialization of this technology. Fortunately, novel techniques to provide oxygen to the fuel have recently been developed to improve energy efficiency and reduce costs of the system. (Chen et al., 2015; Duan & Li, 2023)

2.1.2. Carbon dioxide transport

In CCS supply chain, carbon transport is an important link between CO_2 capture and storage (Leung et al., 2014). As illustrated in Figure 2.5, after capture process, the captured CO_2 is normally transported through different possible transport options to a suitable storage site. Previous research shows that CO_2 transport can be carried out by pipeline, ships, trucks, and rail (Al Baroudi et al., 2021; C. Han et al., 2015; Liu et al., 2023; Onyebuchi et al., 2018; Wildbolz, 2009). Among these, pipeline and ships can be utilized for offshore transport, while onshore transport includes pipeline, trucks, and rail (C. Han et al., 2015; Lu et al., 2020). As affirmed by Liu et al. (2023), the amount of CO_2 captured and distance between capture and storage sites are most essential to choose CO_2 transport modes. Owing to the ability to transfer large volume of CO_2 over a long distance, pipeline and ships are considered as the most popular and economical CO_2 transport options (Munkejord et al., 2016; Wildbolz, 2009). Conversely, trucks and rail are less frequently used in CCS projects and receive less attention from academic (Al Baroudi et al., 2021; C. Han et al., 2015).

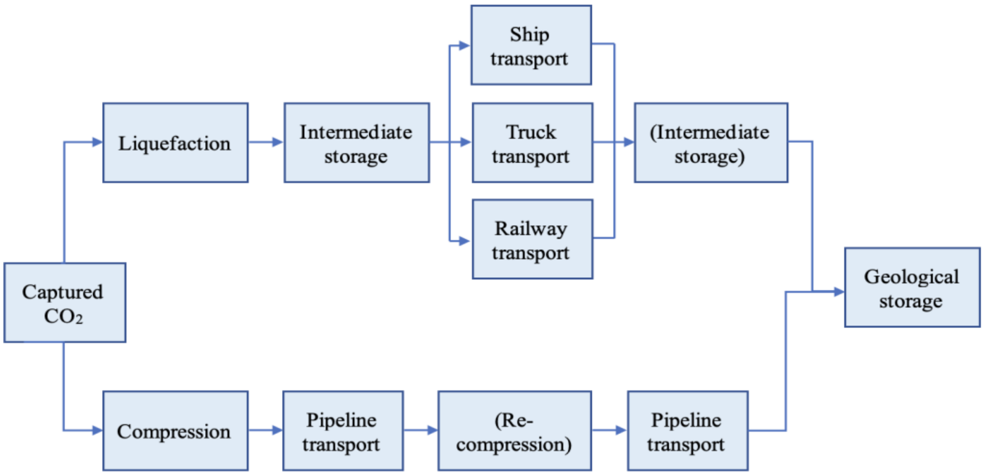


Figure 2.5. CO_2 transport system *(synthesized by authors)*

2.1.2.1. Pipeline

As summarized by Lu et al. (2020), CO_2 transported via pipeline is not a new research topic, it has been existing since the 1970s. Pipeline transport in terms of economic performance, transport process and pipeline design are three most popular topics in CO_2 pipeline transport research. Many reports show that among all possible transport options for CO_2, pipeline transportation has the potential to carry the largest amount of CO_2 (Boot-Handford et al., 2014; Leung et al., 2014; Metz et al., 2005). According to Lu et al. (2020), and Metz et al. (2005), the investment cost of pipeline facilities is high. However, as there are a limited number of steps involved in the transport process, pipeline transport has low operation cost (Ansaloni et al., 2020). Besides, the economies of scale has a considerable impact on the pipeline transport cost as the unitary transport cost of pipeline decreases rapidly when transporting a large volume of CO_2 (Rubin et al., 2015). As a result, pipeline is generally considered as the most advantageous mode, in terms of cost, to transport large volume of CO_2 (Neele et al., 2017; Roussanaly, Jakobsen, et al., 2013; Svensson et al., 2005).

With regard to transport process, CO_2 is usually transported via pipeline in single-phase to avoid pipe cavitation happening when CO_2 changes from one phase to others. According to Liu et al. (2023), CO_2 can be transported by pipeline under gas phase, liquid phase, dense phase, and supercritical phase. Owing to the different requirement of each phase, suitable compressors, pumps, or heat exchangers need to be installed in the pipeline transport system to maintain the single-phase flow and avoid pressure drop along the pipeline route. Figure 2.6 shows different pipeline system suitable for each CO_2 phase.

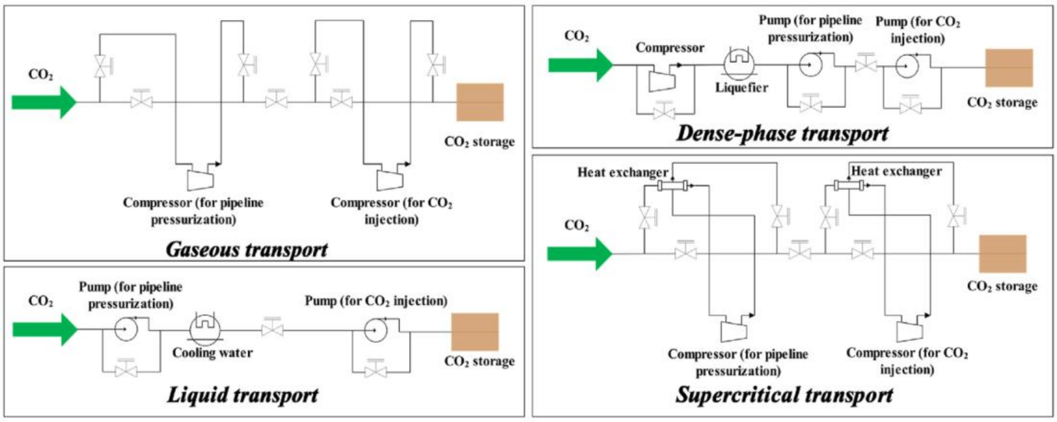


Figure 2.6. Different pipeline system suitable for each CO_2 phase *(Zheng et al. (2018) cited in Lu et al. (2020)*

Based on experiments and practical evidence, many authors, such as Liu et al. (2023), Lu et al. (2020), and H. Wang et al. (2019), have showed that gas and liquid transportations are suitable for low throughput and short-distance pipeline, while dense and supercritical transportations are more suitable for long-distance pipeline. In addition, dense and supercritical phases are more efficient and economical (Lu et al., 2020). For CO_2 to be transferred under dense or supercritical phases, the pressure and temperature ranges should be 85 – 150 bar and 12 – 44^{o}C respectively (Forbes et al., 2008; C. Han et al., 2015; Serpa et al., 2011).

When it comes to pipeline design, construction of pipeline depends on natural conditions. For example, implementing pipeline transport is likely infeasible in regions frequently affected by natural calamities (Nam et al., 2013); or construction becomes more difficult and costly in mountainous areas. Additionally, Liu et al. (2023) state that the length of pipeline should be minimized to optimize construction and operation cost since longer pipeline route will raise the investment cost.

2.1.2.2. Ships

For offshore CO_2 transport, ship has emerged as a potential method as it provides flexible routes between capture sources and storage sites (Zahid et al., 2015). Publicly available research on CO_2 ship transport was first found in the early 2000s with a Japanese patent of Mitsubishi Heavy Industries (Mitsubishi, 2002). This patent confirms that CO_2 can be transported by ships through applying well-established technologies developed for liquefied petroleum gas (LPG). Since then, the number of studies on CO_2 ship transport has been increasing considerably. Among them, about 60% have been identified since 2010 (Brownsort, 2015). Research has been mainly from Europe and the Far East (Aspelund et al., 2006; Brownsort, 2015). As of 2015, 60% of studies related to CO_2 shipping was from Europe, while 35% came from the Far East (Brownsort, 2015). Most of the published research consider technical and economic aspects of CO_2 shipping.

Regarding technical feature of CO_2 ship transport, owing to its discontinuous characteristics, intermediate storage must be implemented in its value chain to handle the captured CO_2, making CO_2 shipping value chain longer compared to the pipeline (Ansaloni et al., 2020; Brownsort, 2015; Mitsubishi, 2004; Wildbolz, 2009). SINTEF et al. (2018) illustrate different components of the CO_2 shipping process (Figure 2.7). In this process, the captured CO_2 is first liquefied, then stored in intermediate storage tanks before being loaded onto ships. The shipping carriers will then complete the process by reaching final storage sites or onshore port terminals. Among these steps, liquefaction and unloading receive more attention from researchers.

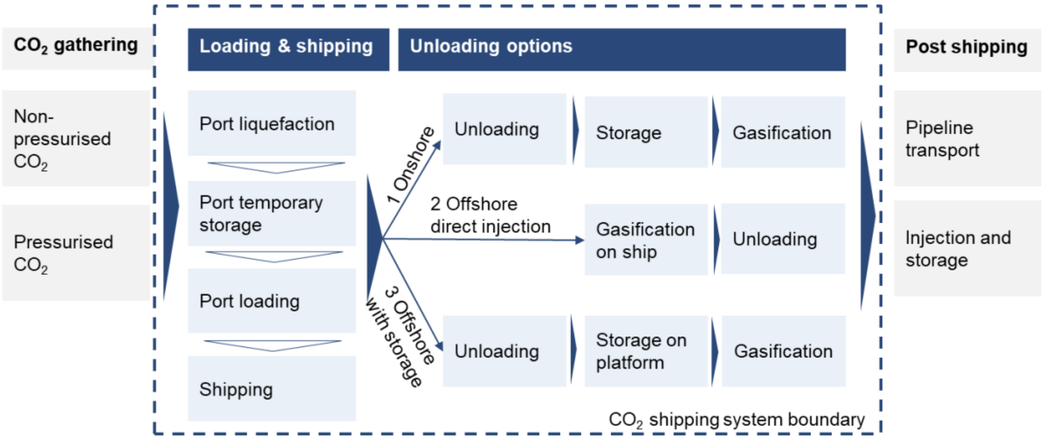


Figure 2.7. Components in the CO_2 shipping chain *(SINTEF et al., 2018)*

Liquefaction is an indispensable step in the CO_2 shipping process to bring the captured CO_2 to suitable conditions before transporting. Most of the existing studies recommend that 7 bar and -50°C is preferred condition for CO_2 ship transport to obtain high-density state of CO_2 and lower capital cost of the method (Aspelund & Jordal, 2007; Liu et al., 2023; Metz et al., 2005; Øi et al., 2016). Additionally, liquefaction is the most energy consuming part of the CO_2 shipping chain. Particularly, liquefaction needs 77% of the total energy required of the whole CO_2 shipping chain (Aspelund et al., 2006), or 10% of the total energy consumption of the entire CCS system (U. Lee et al., 2012), and it is even 11-14% more energy intensive than pipeline conditioning (Aspelund et al., 2005).

Concerning unloading options, many studies indicate that CO_2 transported by ships can be unloaded either onshore or offshore (Al Baroudi et al., 2021; Brownsort, 2015; SINTEF et al., 2018). In case of onshore unloading, the ships arrive at a port terminal and then CO_2 is unloaded to the intermediate storage prior to being heated and pumped to suitable conditions for pipeline transmission to final destination (Yoo et al., 2013). With offshore unloading, two alternatives are unloading onto a platform with storage or direct injection from ships. The first option is offloading the CO_2 to offshore platforms (or floating storage and injection (FSI) hubs) in which it is stored prior to injection to storage sites. For direct injection, the CO_2 is conditioned on board and transferred to the storage sites through injection wells. While onshore unloading is well established through extensive matured knowledge in port-to-port shipping of LPG, offshore unloading is still a novel process, in both academia and industry, and poses some technical challenges associated with its implementation. (Al Baroudi et al., 2021)

In relation to economic aspect of CO_2 shipping, most of the research conducts cost analysis of CO_2 ship transport in comparison with pipeline transport. Roussanaly, Hognes, et al. (2013) carry out a multi-criteria analysis of shipping and pipeline as different transport options for 10 Mt CO_2/year and reveal that while pipeline shows the lower indicator regarding operation expenditure, shipping is more advantageous in terms of capital cost. Roussanaly, Jakobsen, et al., (2013) concluded that for a fixed amount of CO_2, pipeline is favored to transfer CO_2 over a shorter distance. Besides, Zero Emission Platform (ZEP) (2011) investigated cost of CO_2 transport with capacity of 2.5 Mt CO_2 per annum and discovered that unit transport cost is 45% lower for pipeline than ship considering a distance of 180 km; however, unit shipping cost is 27-62% lower than that of pipeline with a distance of 500 – 1500 km. IEAGHG (2020) examined unitary carbon transport cost for different flow rates and reported that while shipping is 64% and 10% less expensive than pipeline in transporting 0.5 and 2 Mt CO_2/year respectively, pipeline transport is 24% cheaper than shipping at 5 Mt CO_2/year. In summary, many studies agree that CO_2 shipping is more attractive than pipeline option to transport smaller CO_2 volume over longer distance (Aspelund & Jordal, 2007; Brownsort et al., 2015; Munkejord et al., 2016; ZEP, 2011).

2.1.2.3. Trucks and rail

Trucks and rail are other possible modes to transport CO_2. Although truck and rail transport do not require specific investment in construction of transport facilities (Lu et al., 2020), they can carry much lower capacities than pipeline and ship transport (Wildbolz, 2009). Additionally, the limitation in route choice of railway and high operation cost of trucks make these options rarely be used in large-scale CCS projects.

However, there still exists some research on CO_2 transport via trucks and railways. Wildbolz (2009) describes that trucks and rail are feasible options to transport CO_2 where CO_2 is required to be under liquid phase at 20 bar pressure and -20°C temperature. Metz et al. (2005) indicate that truck-based and rail-based transport are less mature than pipeline or ship but can be applied using similar tanker condition of ship transport. Roussanaly et al. (2017) evaluate the potential of railway CO_2 transport by comparing operating costs of pipeline and railway transport in different project scenarios. This research shows that railway transport system could represent a viable option to pipelines for medium to long distances, especially in cases where additional conditioning costs of railway transport are limited or in case financial risk is important for decision-making. Few other studies, such as Gao et al. (2011), and J.-H. Han & Lee (2012), considered trains and trucks as alternatives of CO_2 transport and concluded that they are economically infeasible, especially in large-scale CCS projects, in comparison to pipelines and ships. However, Metz et al. (2005) and McLaughlin et al. (2023) still believe that on large scale system, trucks and trains are still potential alternatives, for example trucks or rails can be utilized in an intermediate step to transport CO_2 to port terminals of ship carriers.

2.1.3. Carbon dioxide storage

Geological carbon storage involves injecting CO_2 into deep rock formations to store it permanently (Newell & Ilgen, 2019). The injection of CO_2 implements longstanding practices and technologies that have been deployed by the oil and gas industry for enhanced oil recovery. According to Hosseini et al. (2013), injection technology, well-drilling technology, computer simulation of reservoir dynamics and monitoring methods during and post-injection to maintain safety and detect potential leakage can be adjusted from existing applications to apply for geological sequestration of CO_2.

In order to store CO_2, geological formations need to have certain characteristics. For example, they should be deep enough and be overlain by a satisfactory sealing cap rock to prevent CO_2 from migrating upward. In addition, the subsurface formation is required to have adequate thickness (storage capacity), porosity and permeability (injectivity) to keep large amounts of CO_2. The geologic storage options include unmineable coal seams, mined salt domes, deep saline aquifers and active or depleted oil and gas reservoirs. Comparatively, deep saline aquifers and active or depleted oil and gas reservoirs have been considered as the best sites for large-scale removal of CO_2 (Raza et al., 2018). Details about advantages and disadvantages of each option are summarized in the Table 2.1. (Solomon et al., 2008; Newell & Ilgen, 2019)

Geological storage options	Advantages	Disadvantages
Coal seams	• Large capacity • Enhanced methane production	• High cost • Geographically limited
Salt domes	• Custom design • Safety	• High cost • Geographically limited
Saline aquifers	• Large capacity • Widespread availability	• Unknown safety
Active or depleted oil and gas reservoirs	• Proven safety • Infrastructure in-place • Enhanced hydrocarbon recovery	• Geographically limited • Problems with multi-phase flow • Might not be available for immediate injection

Table 2.1. Comparison of different geological storage options *(Saeedi & Rezaee, 2012; Raza et al., 2018)*

2.1.4. CCS deployment opportunities

The goal of limiting temperature increase to 1.5°C by 2050 of the Paris Agreement has sparked a growing interest in CCS from both academia and industry. Although the development of CCS is facing many challenges, there still exists some opportunities for expansion of CCS system. These opportunities include potential storage resource, supportive policies, and funding mechanisms.

2.1.4.1. Potential storage resource

As questioned by Filippov & Zhdaneev (2022), an important issue to expand global CCS system is whether there is available sufficient capacity to reliably store enormous CO_2 volume underground. According to Martin-Roberts et al. (2021), to meet the target of the Paris Agreement, approximately 5.6 Gt CO_2 per year are required to be captured and stored using CCS technologies by 2050. In other words, the total storage capacity should be at least 450 Gt CO_2 to store the required amount to the end of the 21st century.

Fortunately, there are enough geological resources to reliable store CO_2 for at least several centuries ahead (Filippov & Zhdaneev, 2022). The CO_2 Storage Resource Catalogue (CSRC), a program built to review the commercial readiness of CO_2 storage resources all over the world, conducted a report assessing over 800 potential CO_2 storage resources in both saline aquifers and oil and gas fields (OGCI et al., 2022). This report discovers that the total global potential storage resources are 13954 Gt CO_2, of which commercial projects, including sites where CO_2 storage is approved to develop or is already in process, only contribute 0.25 Gt (nearly 0.002%) and undiscovered places account for 13377 Gt CO_2. Additionally, these potential resources are available in almost all regions of the world. As a result, this presents a huge potential for the development of CCS system.

2.1.4.2. Supportive policies and funding mechanisms

Supportive polices and suitable funding mechanisms play an important role in the development of CCS over the past decades. In fact, almost all CCS projects, either operating or in construction, have received positive financial investments (Global CCS Institute, 2020b). Although the number of favorable policies and funding programs for CCS is still limited, it has been increasing recently. This growing investment has contributed to an increasing number of CCS projects throughout the world. The most common policies have been used to support CCS are tax credits, carbon pricing and grant support (Zapantis et al., 2019).

a. Tax credits

Tax credits supplement revenues for CO_2-EOR projects, providing incentives for developing geological storage sites of CO_2 (Zapantis et al., 2019). The United States is the first country applying this method to finance six large-scale CCS projects since 2011 (Global CCS Institute, 2020b). Particularly, this tax credit, known as Section 45Q, provides a remarkable boost to CCS investment. This credit was expanded in 2018 to allow smaller scale CCS project to qualify for the credit. It now offers up to \$50/tCO_2 for CO_2 storage sites. (IEA, 2020b)

b. Carbon pricing

Carbon pricing is an alternative approach to place a value on emission reduction, encouraging the development of CCS (Zapantis et al., 2019). The foremost carbon tax launched in Norway in 1991 has succeeded in incentivizing the growth of Snøhvit and Spleiner CCS projects. At \$17/tCO_2, the total unit cost of the Spleiner project was less than tax penalty of \$50 for a tonne of CO_2 emitted to the atmosphere, making CCS project more favorable (Herzog, 2016).

c. Grant support

Grant support for CCS can be provided through many ways. One way some governments used to enable CCS projects is to support the construction of CCS facilities through State Owned Enterprises (SOEs) (Zapantis et al., 2019). For example, China has invested in CCS through the state-owned company CNPC for the Jilin CCS project. This method can bring the capital cost of the CCS project down as SOEs can borrow at low interest rates (Zapantis et al., 2019). Another way of grant support is through funding programs. For instance, the EU Innovation Fund makes up to EUR 10 billion available to support the demonstration of low-carbon technologies, including CCS technologies; or the UK government established a CCS infrastructure fund of GBP 800 million to support CCS projects (IEA, 2020b).

2.1.5. CCS deployment challenges

The literature review reveals that there exist several CCS large-scale deployment barriers which can be grouped into four main areas: (i) Technical challenges, (ii) Economic challenges, (iii) Policy and regulation and (iv) Social acceptance. In this part, we will focus on the last three non-technical barriers since reviews by Budinis et al. (2018) and Leiss & Krewski (2019) show that there are no major purely or intractable technological barriers to the successful widespread CCS implementation. Indeed, CO_2 separation, transport and injection have been commonly used for many years in the oil and gas industry. However, more research and development is required to reduce the energy penalty, improve the capture rates and optimize the integration of three CCS components (Zeipen, 2020).

2.1.5.1. Economic challenges

Cost of CCS is one of the major hurdles affecting its widespread deployment (Budinis et al., 2018). CCS requires large capital investment in long-lived assets. Besides capture facility that makes up the largest proportion of the total costs of CCS (Leeson et al., 2017), those assets include geological storage resources and CO_2 transport infrastructure that cost a lot of money to build and develop. In fact, estimating the actual cost of CCS and expressing it clearly is a challenging task owing to lack of empirical data and difficulty in setting the baseline to compare different CCS facilities (Karayannis et al., 2014; Budinis et al., 2018).

Apart from the high cost, there are insufficient financial incentives for the uptake of CCS. Although the carbon price is applied in some markets, it generally has low values that do not reflect the true cost of CO_2 emissions, making CCS economically unattractive. In other words, the market fails to create viable business cases for CCS, and investment in CCS thus largely depends on policy incentives and public funding (Zeipen, 2020). In Europe, ETS was adopted as a market-based method to decrease CO_2 emissions, yet it is not enough to drive investment in CCS from industrial partners (Gassnova, 2020). To address economic obstacles, more R&D endeavors are needed to reduce costs and more consistent and rigorous carbon pricing mechanisms should be in place to level the playing field for CCS and other low-carbon alternatives (Zeipen, 2020).

2.1.5.2. Policy and regulation

Several policy and regulation challenges related to CCS have been discussed in the literature. CCS projects encompass various stakeholders, such as plant owners, CO_2 transporters and storage site operators, who must adhere to diverse legal requirements and regulations concerning environmental preservation, health and safety, property rights and monitoring. However, there is a lack of clear, consistent and comprehensive policy frameworks exclusively tailored for CCS. A noticeable shortcoming is the lack of established legal frameworks pertaining to liability for possible leakage or accidents during the long-term storage of CO_2 in most jurisdictions. This creates uncertainty for CCS project developers and thus discourages investment in CCS. (Leiss & Krewski, 2019; Zeipen, 2020).

Moreover, other policy and regulation barriers that can hinder the widespread implementation of CCS include inconsistent and uncertain carbon pricing as discussed in the previous part, limited dedicated funding mechanisms specifically designed for CCS and ambiguity in regulatory approvals which causes delays and cost increases. It is imperative to have clear and supportive policies, stable carbon pricing mechanisms, dedicated funding and streamlined regulatory processes to surmount these obstacles and promote CCS deployment. (Romasheva & Ilinova, 2019; Akerboom et al., 2021)

2.1.5.3. Social acceptance

Concerns about public acceptance due to perceived risks and limited awareness of CCS have been identified as significant obstacles to its deployment, as highlighted by industry, government, and environmental non-governmental organization advocates (Leiss & Krewski, 2019; Ashworth et al., 2015; Federico d’Amore et al., 2020). Often, apprehensions are about the safety issues related to the potential hazards arising from the CCS operation and the possibility of CO_2 leakage threatening nearby communities, commodities and the environment (Yang et al., 2016). Thus, the public might view CCS as a last resort, favoring the utilization of other low-carbon technologies such as renewable energy (L′Orange Seigo et al., 2014). Addressing this social challenge therefore requires bridging the gap between expert and public perception of risks related to CCS through effective communication, public engagement and educational campaigns (Federico d’Amore et al., 2020).

2.2. Supply chain network design

Supply chain network design (SCND) allows simulating and visualizing supply chains to ultimately optimize them and improve their performance. With the increasing importance of adding values to supply chains, SCND recently is getting more attention from both academia and industry. Thus, many studies have been conducted, providing insights into this topic. To gain a thorough knowledge about SCND, in this section, a review of relevant literature about supply chain, definition, and role of SCND, and SCND optimization problem will be provided.

2.2.1. Supply chain

The concept of supply chain has become familiar to both practitioners and academics since the early 1980s. In 1982, the supply chain term was initially defined by professional consultants Oliver and Webber as a network of companies that are involved in different activities and processes, through downstream and upstream linkages, to create values in the form of both products and services and deliver them to the ultimate consumer (Oliver and Webber, 1982, cited in Martins & Pato, 2019). This definition relates a supply chain to multiple parties, material and immaterial activities, vertical connection, and value creation. In line with this explanation, Mentzer et al. (2001) also describe supply chain as the set of multiple entities that are directly involved in the downstream and upstream flows of products or services, finances, and information from a source to final customer.

While the supply chain term has not changed much over time, it has been interpreted more concisely with clearer explanation of involved parties. According to Chopra & Meindl (2016, p. 13), a supply chain "consists of all parties involved, directly or indirectly, in fulfilling a customer request". In other words, the supply chain consists of not only the suppliers and manufacturers, but also retailers, warehouses, transporters, and even consumers (Chopra & Meindl, 2016). Chopra & Meindl (2016) also point out that within each party, the supply chain contains all functions related to receiving and filling customers' demands, including but not limited to marketing, product development, distribution, operation, and customer service. This emphasizes that a supply chain has both vertical and horizontal connections. In addition, they assert that the overall objective of every supply chain should not be to minimize supply chain costs only, but to maximize the total value generated.

Inseparable from the supply chain concept is the term supply chain management. According to Oliver and Webber (1982) cited in Martins & Pato (2019), supply chain management is the process of planning, implementing and managing the operation of the whole supply chain to satisfy customers' demands as efficiently as possible. Despite sometimes being used interchangeably, supply chain and supply chain management are different subjects since supply chain still exists whether it is managed or not (Mentzer et al., 2001).

2.2.2. Definition and role of SCND

Farahani et al. (2014) explain supply chain network design (SCND) as the activity of designing an efficient and effective physical network structure for a new supply chain or re-constructing an existing network of a supply chain to increase its overall value. This definition is strengthen by Govindan et al. (2017) as they believe that SCND determines infrastructure and physical structure of a supply chain. Since the structure of the supply chain has a significant impact on its overall costs, competitiveness, and performance (Shen, 2006), SCND is recognized as one of the most important elements affecting the effectiveness of the whole supply chain (Farahani et al., 2014). In the same vein, Amir Mohammad et al. (2017) believe that SCND plays an essential role in creating competitive advantages and improving performance of the supply chain and influences other decisions of the supply chain over time. Further, as highlighted by Simchi-Levi et al. (2003), SCND remarkably impacts the overall costs (profits) of the supply chain. In addition, Waltho et al., (2019) affirm that SCND also plays a crucial role in shaping the environmental impact of the supply chain.

2.2.3. SCND optimization problem

SCND optimization problem concerns a computational process to find the best of all possible supply chain network in terms of cost, risk or other values based on perspective of decision-makers. Due to the role of SCND in improving performance of a supply chain, SCND optimization problem has received a growing interest from academic in recent years (Dzupire & Nkansah-Gyekye, 2014). In this part, relevant literature about objectives and decisions of SCND optimization problem, and models solving SCND optimization problem is displayed.

2.2.3.1. Objective of SCND optimization problem

There are many different objectives in SCND optimization problem, such as minimizing total network cost, maximizing customer service, or minimizing environmental impacts. However, most of the research on SCND problem targets at economic performance, such as minimizing the total cost or maximizing the total profit, of not just one single entity but rather the entire supply chain as the objective of SCND (Babazadeh et al., 2017; Hajiaghaei-Keshteli & Fathollahi Fard, 2019). In other words, minimizing the total system cost and maximizing profits are considered as the ultimate objectives of SCND optimization problem (multi). Moreover, the objectives in SCND are sometimes conflicting in nature. For example, the objective of maximizing customer service or minimizing environmental impacts generally leads to an increase in total expense, conflicting with the objective of minimizing total system cost.

2.2.3.2. Decisions of SCND optimization problems

SCND is considered as a long-term strategic decision (Lahri et al., 2021). There are many decisions made in designing an optimal supply chain network. According to Dzupire & Nkansah-Gyekye (2014), the decisions in SCND problems include what product, how much, when and where to produce and from where, how much and when to buy materials. Particularly, Chopra & Meindl, (2016) classify decisions in SCND problem into four categories: firstly, *facility role*, which answers questions what is the role of each facility and what activities are operated at each facility; secondly, *facility location*, which determines where facilities should be located; thirdly, *capacity allocation*, which concerns how much capacity should be assigned to each facility; finally, *market and supply allocation*, identifying which markets each facility should serve and which sources should supply each facility.

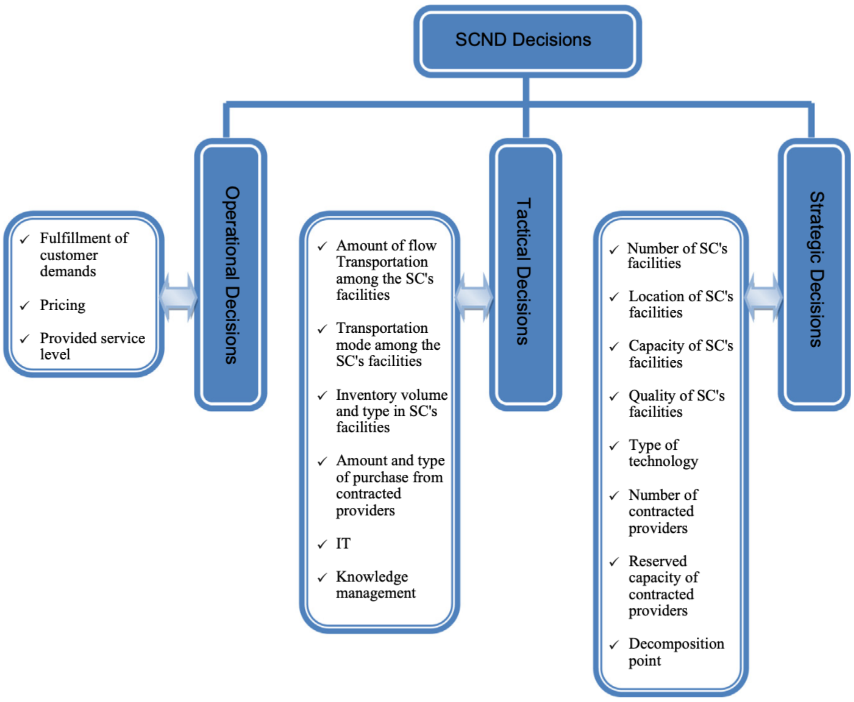


Figure 2.8. Three levels of SCND decisions *(Farahani et al., 2014)*

Further, as emphasized by Hajiaghaei-Keshteli & Fathollahi Fard (2019), choosing suitable facilities among all potential locations, identifying numbers and capacities of each facility as well as flow through the network are the main and most vital decisions in SCND optimization problem. Farahani et al. (2014) also agree that there is a wide range of decisions needed to make in SCND optimization problem, including number, location, and quantity (and quality in some cases) of located facilities and flow among them. Additionally, they divide these decisions into three level according to their time span: operational, tactical, and strategic decisions. Strategic decisions are typically made for three to five years, tactical decisions are often constant for three month to three years and operational decisions are normally hold for shorter periods (Govindan et al., 2017). It is worth noting that holding those decisions for a certain period depends mostly on the nature of a supply chain and accordingly, it can change for different supply chain networks. Different decisions of each level are demonstrated in Figure 2.8 above.

According to Chopra & Meindl (2016), decisions in SCND optimization problem would significantly influence the performance of the supply chain, for instance, a good facility location choice can increase a supply chain's responsiveness while reducing its total costs. Among many different SCND decisions, locating facilities in each tier of the supply chain is likely to be the most popular and important decision (Farahani et al., 2014). This is because determining suitable locations of facilities seems to be the decision at the highest level in SCND and any change in this decision influences other decisions in lower levels.

a. Factors affecting decisions in SCND optimization problem

The decisions in SCND optimization problem are not always easily made as they are affected by a wide range of factors. The difficulty in making SCND decisions can be explained by that while some factors have a linear impact on SCND, others are more complicated to model, especially if they are combined in one model (Waltho et al., 2019). According to Chopra & Meindl (2016), there are eight main elements influencing the decisions in SCND problem, which are: (1) *strategic factors*, requiring the SCND decisions to be relevant with general strategy of each party within the supply chain; (2) *technological factors*, concerning the match of the SCND decisions and available technologies; (3) *macroeconomic factors*, including tariffs, taxes, shipping costs, exchange rates and demand risk; (4) *political factors*, affecting location decision the most; (5) *infrastructure factors,* concerning the availability of labor, proximity to transportation terminals, seaports and airports, rail services, congestion, and highway access; (6) *competitive factors*, placing the necessity of considering competitors' strategy when designing a supply chain network; (7) *customer response time and local presence*, stating that local availability and customers' preferences can change the SCND decisions; and (8) *logistics and facility costs*, changing when the number of facilities, their capacity and location change, for example, transportation costs reduce when the number of facilities raise.

2.2.3.3. Model solving SCND optimization problem

There are many models that have been used to examine SCND optimization problem, namely continuous approximation (CA), stochastic mixed integer programming (SMIP), fuzzy mixed integer programming (FMIP), mixed integer nonlinear programming (MINP) or mixed integer linear programming (MILP), etc. Among these models, most of the studies have employed mixed integer programming (MIP) models to investigate their research on SCND (Hajiaghaei-Keshteli & Fathollahi Fard, 2019). A MIP model consists of: (1) objective function(s), expressing the purpose of the model; (2) a mix of integer and continuous variables, concerning the decisions of the model; and (3) a set of constraints, placing condition for each variable and restrictions on the system (Kuo et al., 2016). This model can vary from simple single objective to complex multi-objective models.

Regarding single objective model, this is the most popular model used to investigate SCND problem (Hajiaghaei-Keshteli & Fathollahi Fard, 2019). Georgiadis et al. (2011) develop a MILP with the objective of minimizing total cost to design an optimal supply chain network under uncertain demand. Soleimani & Kannan (2015) apply a mixed integer nonlinear programming (MINLP) model to investigate closed-loop SCND in large-scale networks. Moreover, Chopra & Meindl (2016) introduce two MILP models supporting decisions of facility location and capacity allocation: firstly, *gravity location model*, determining a location that minimizes transportation costs but not accounting for other costs; secondly, *network optimization model*, which is useful when choosing facilities and allocating capacity and markets to facilities.

Regarding multi-objective model, Wang et al. (2011) propose a two-objective model to balance the environmental impacts and the total costs of SCND. Pishvaee et al. (2012) develop a FMIP with two-objective model to minimize both the total costs and the environmental impacts for a forward supply chain network. Pishvaee et al. (2010) exploit a MILP model for designing a reverse logistic network by examining both transportation and opening costs. Devika et al. (2014) apply a MILP model with three objectives to design a sustainable supply chain network based on triple bottom line approach. Very few studies on SCND have more than three objective functions (Fragoso et al., 2021). For example, to manage solid waste in Northern Greece, Erkut et al. (2008) build up a SCND model with five objectives, namely minimizing total system cost, minimizing environmental impacts subjected to greenhouse gas emissions, energy, landfill and materials recovery.

2.3. SCND for CCS

Mathematical programming techniques such as MILP, MINLP, and multi-objective optimization (MOO) have been recently deployed in literature to support designing and implementing optimal supply chain networks for CCS at different scales, ranging from region-wise, nation-wise to continent-wise. (Tapia et al., 2018; Hasan et al., 2022). Table 2.2 presents a summary of research on the optimization of CCS supply chain networks.

2.3.1. SCND for CCS at continent-wide scale

Some research has been done on the optimization of CCS supply chain networks at continent-level, mainly in Europe. In 2011, Kjärstad et al. examined cost and possibilities to develop an integrated CCS network among six countries in northern Europe, including Czech Republic, Belgium, Netherlands, Poland, Germany, and Slovakia. They found out that the most important factor affecting the pipeline system is the phase-in of capture plants. Furthermore, if countries such as the Czech Republic, the Slovak Republic and Poland have less storage capacity than estimated, CCS will not an economically feasible option for these countries to reduce emissions due to the long transport route to other storage sites. Morbee et al. (2012) built InfraCCS model to determine the cost of the optimal CO_2 transport network through a pipeline-based infrastructure at Europe-wide scale for the period 2015-2050. This model is made possible by using some methodological innovations in comparison to previous studies, including using k-mean clustering to reduce number of nodes, and applying the Delaunay triangulation algorithm to pre-select pipeline route. This paper states that international coordination plays a crucial role in the development of an optimal trans-European CO_2 transport network.

Further, d’Amore & Bezzo (2017) presented a MILP model for the strategic planning and design of a large European CCS supply chain over a time horizon of 20 years. The purpose is to find the scale and geographic location of capture and storage sites as well as the most suitable transport means and routes for an economically optimized overall network. However, this paper considers only power plants as CO_2 emission sources. This work was subsequently improved and updated by incorporating assessment of different risk sources into the modelling framework, such as societal risk caused by leakage (d'Amore et al., 2018) and economic risk due to uncertainty on geological storage availability (d'Amore et al., 2019a, 2019b). Specifically, d'Amore et al. (2018) added societal risk constraints to the model to ensure that the local risk level is less than a pre-set threshold. Meanwhile, d'Amore et al. (2019a) quantified the financial risks emerging from geological uncertainty, while minimizing storage risk exposure.

According to Federico d'Amore et al. (2020), the public perception of the employment of CCS technologies is still unclear, and opposition can lead to delays or cancellations. Thus, a multi-objective MILP is proposed in designing the Europe-wide CCS supply chain to simultaneously address and balance two objectives: cost minimization and social acceptance maximization. Recently, d'Amore et al., (2021a) and d'Amore et al. (2021b) introduced a comprehensive model to optimize a European-scale CCS supply chain network from a wide range of emission sources including power, cement, steel and refining sectors. A noticeable difference between two papers is that while d'Amore et al., (2021a) only takes into account pipeline as the only transport mean, d'Amore et al. (2021b) also considers ship besides pipeline when modelling the transport infrastructure.

Besides, SCND for CCS in Asia has recently received certain attention. Dasari et al. (2022) evaluated the feasibility of CCS in Southeast Asia and presented a model to compute the optimal CCS network with the objective of minimizing the total cost. This research employs "a source-sink mapping methodology" in relation to many CO_2 transport modes, including offshore pipelines, ships, and onshore pipelines. The paper first examines the potential CO_2 storage sites in ASEAN countries and proposes that this area has the potential to provide sufficient capacity to store CO_2 in the region for several decades. Then, it investigates the optimal CO_2 transport network by using a case study with CO_2 sourced in Singapore and transported to regional storage sites via pipeline or ships. The result of this study shows that CO_2 ship transport is more cost effective than pipeline for smaller CCS system and longer distances.

In general, papers analyzing continent-wide CCS supply chains all consider pipeline or ship as possible transport means. According to Middleton & Bielicki

(2009), pipeline is the only economical way for transporting large volumes of CO_2. Given the high-volume flowrates required by significant CO_2 sources at a continental scale, it makes sense that the CCS infrastructure mainly places on offshore or onshore pipelines to connect CO_2 sources and/or storage nodes. Besides, CO_2 transported by ship is emerging as a cost-effective alternative compared to offshore pipelines in some circumstances. Ship-based transport also offers flexibility to connect harbours or to connect onshore docks with offshore sequestration basins directly. (d'Amore et al., 2021b)

2.3.2. SCND for CCS at nation-wide scale

CCS supply chain optimization problems at national scale have been developed in recent years. Hasan et al. (2015) introduced a multi-scale framework to design CCUS supply chain network in the United States with the goal of minimizing net cost, which is the difference between the total system cost and the revenue or benefits gained from CO_2 utilization for enhanced oil recovery (Hasan et al., 2022). To devise extensive supply chain networks for CCUS and CCU in the United States, the study considers various factors such as the choice of sources, capture materials, capture processes, CO_2 pipelines, locations of storage and utilization sites, as well as the amounts of CO_2 stored. Each process of CO_2 capture is optimized and the most superior materials are identified from a wide variety of candidate materials. Through the optimized CCUS supply chain network, it is potential to achieve a 50% reduction in total stationary CO_2 emissions across the United States, which comes at a cost of \$35.63 per ton of CO_2 captured and managed.

In Asia, CCS is often studied in China and South Korea. Kim et al. (2018) proposed a MINLP model to design an optimal CCS pipeline network in South Korea in consideration of various practical factors such as geographical conditions, population density, uncertainty of national policies and the reservoir capacity. The findings of this study demonstrate that a more comprehensive network can be achieved by incorporating penalty factors that correspond to various geographical conditions. Moreover, the research suggests that alongside the explicit examination of potential sequestration sites, the development of effective CCS policies such as offering financial incentives to plants participating in the CCS network is crucial for cost-effective network construction.

In 2020, Wang et al. evaluated the least-cost layout of CO_2 sources and sinks, as well as cluster development opportunities for CCS in the entire China under the 2°C constraint. However, this paper considers only coal-fired power plants as CO_2 sources. The findings of this study reveal that 165 existing coal-fired power plants in China need retrofitting with CCS technology to meet the climate target. The total amount of CO_2 captured is estimated to be 17.42 billion tons, and there are three storage basins that have the potential to store about 90% of the captured CO_2. The estimated total mitigation cost is USD 1212 billion, and the revenue from CO_2 utilization is USD 377 billion.

In the UK, Elahi et al. (2014) proposed a multi-period spatially explicit economical optimization model of an integrated CCS infrastructure using the MILP tool developed in GAMS. The solution shows the operational approach and investment requirement for all three elements of the CCS supply chain across multiple phases. By analyzing four time periods leading up to the year 2050, the research illustrates the progressive development and transformation of the CCS system over time. However, Elahi et al. (2014) acknowledged that the proposed solution just presents a deterministic view of the development of the CCS system, which might overlook the inherent uncertainties and risks associated with its implementation. Thus, Elahi et al. (2017) improved the model to a stochastic optimization tool where the results are presented in the form of flexible strategies in the face of uncertainties. Here, uncertainties in the storage capacity and the financial market are taken into consideration. In the same vein, Nie et al. (2017) presented a real options analysis of CO_2 transport and storage in the UK considering regulatory, market, technical and geological risks and uncertainties, helping regulators and investors effectively evaluate incentives for CCS employment at large scale.

When it comes to Europe, there are some contributions for Norway, the Netherlands, Turkey, Germany and Switzerland. Klokk et al. (2010) designed a model to maximize the net present value for the whole CO_2 value chain. Five CO_2 sources, two aquifers and 14 oil fields with EOR potential in Norway are considered to illustrate the suggested model. Ravi et al. (2017) aimed at minimizing the overall cost for a nationwide CO_2 emission reduction in the Netherlands through selecting appropriate sources, capture technologies, CO_2 storage sites and pipeline networks. The foremost finding of this research is that the capture and compression contribute to a large share of the cost.

Ağralı et al. (2018) built a MILP optimization model for CCS/CCU versus carbon trading for fossil-fired power plants in Turkey. The model's objective is to minimize the net present costs. Its main constraints are the capacities of the storage sites, the maximum and minimum capacities of various segments within the pipeline network as well as the carbon amount that can be sold to other entities for utilization. The outcome shows that the distance between CO_2 sources and storage/utilization sites and the capacities on the pipes are important factors in choosing between carbon capture and carbon trading. Working on CCUS in Germany, Leonzio et al. (2019) aimed at minimizing the total costs of the supply chain network, which include CO_2 capture and compression costs, storage costs, transportation costs and production costs for different compounds produced from CO_2. One of the findings of this study is that the choice of capture technology and material is influenced by factors such as CO_2 composition, the flow rate of flue gases and the intended final use of the captured CO_2. Particularly, absorption technology proves to be highly effective in capturing high-flow flue gases.

Recently, Becattini et al. (2022) deployed a multi-objective MILP to minimize the total costs of the CCS supply chains of the Swiss waste-to-energy sector while complying with CO_2 emissions targets over a 25 years' time horizon. This contribution considers a variety of transport means including ship, pipeline, barge, truck, and rail. It concludes that pipelines are the most cost-effective mode for transporting large volumes of CO_2. Ship and barge are competitive with pipelines while truck and rail are cost-optimal only when considering small volumes of transported CO_2 or shortsighted time horizons.

2.3.3. SCND for CCS at region-wide scale

One of the earliest works to address full-scale CCS system planning was proposed for Ohio by Turk et al. (1987). With the objective of maximizing the profit, they developed an integer programming model to identify optimal CO_2 allocation for enhanced oil recovery (EOR) in a pipeline distribution network. Utilizing geographical information system (GIS) and mathematical programming, two comprehensive models, SimCCS (Middleton & Bielicki, 2009b) and SimCCS^{TIME} (Middleton et al., 2012) for static and dynamic scenarios, respectively, have been developed to identify pipeline network layout. Particularly, these models spatially and temporally optimize CCS management with a goal of minimizing infrastructure costs while deciding how much, where, and when to capture, transport and store CO_2. While SimCCS was demonstrated using a network of 37 CO_2 sources and 14 storage sites in California, SimCCS^{TIME} was illustrated using data from the Texas panhandle. Also taking a case study in Texas, Yue et al. (2015) adopted a MINLP model for supply chain optimization problem and considered trade-offs between two objectives: total cost minimization and GHG emissions avoided maximization. This study ends with a conclusion that the emitted CO_2 can be stored at a cost of USD 45.52/tCO_2 and nearly 64% of the GHG emissions can be removed from the atmosphere.

J.-H. Han & Lee, (2012) and S.-Y. Lee et al. (2017) did research on CCS supply chains for the region of Pohang in South Korea. Both papers incorporate uncertainty considerations into the modelling framework. A two-stage stochastic programming is used in J.-H. Han & Lee, (2012) to evaluate the effects of uncertainties in operating costs, CO_2 emissions and product prices over a 20-year period (2011 – 2030). S.-Y. Lee et al. (2017) used multi-objective model to minimize the combination of total annual cost, environmental impacts and risks due to uncertainties and they indicate that risk-averse decision makers tend to invest less on capture facilities and produce less product than risk-taking decision makers. In 2020, Zhang et al. developed a MILP model for the cost-optimal supply chain design of CCUS and applied to a case of large emission sources in Northeast China. This study concludes that in general, the optimal CCUS network requires a total cost of USD 23.53 per ton CO_2 and that it is economic feasible to remove 50% of the current emissions from the considered CO_2 sources at an annual cost of USD 2.3 billion accompanied with an annual revenue of USD 0.77 billion from CO_2-EOR.

References	**Objective function**	**Tool**	**Scale**	**Transport mode**	**Note**
(Kjärstad et al., 2011)	-	-	Continent/ Northern Europe	Pipeline	
(Morbee et al., 2012)	Total cost minimization	MILP	Continent-wide/Europe	Pipeline	
(d’Amore & Bezzo, 2017)	Total cost minimization	MILP	Continent-wide/Europe	Ship, Pipeline	CO_2 sources include only power plants. (d’Amore et
(d’Amore et al., 2018)	Total cost minimization	MILP	Continent-wide/Europe	Ship, Pipeline	

(d’Amore et al., 2019b); (d’Amore et al., 2019a)	Total cost minimization	MILP	Continent-wide/Europe	Ship, Pipeline	al., 2018) incorporate societal risk assessment while (d’Amore et al., 2019b) and (d’Amore et al., 2019a) incorporate uncertainty on storage availability into the model
(Federico d’Amore et al., 2020)	Multi-objective: Total cost minimization and community acceptance maximization	MILP	Continent-wide/Europe	Pipeline	Consider only power plants as CO_2 sources
(d’Amore et al., 2021a)	Total cost minimization	MILP	Continent-wide/Europe	Pipeline	
(d’Amore et al., 2021b)	Total cost minimization	MILP	Continent-wide/Europe	Ship, Pipeline	
(Dasari et al., 2022)	Total cost minimization	-	Continent-wide/Southeast Asia	Pipeline, ship	
(Hasan et al., 2015)	Net cost minimization	MILP	Nation-wide/U.S.	Pipeline	
(Kim et al.,	Total cost	MINLP	Nation-	Pipeline	

2018)	minimization		wide/South Korea		
(P.-T. Wang et al., 2020)	Net cost minimization	MILP	Nation-wide/China	Pipeline	Consider only coal-fired power plants as CO_2 sources
(Elahi et al., 2014)	Net present cost minimization	MILP	Nation-wide/UK	Pipeline	
(Elahi et al., 2017)	Total cost minimization	MILP	Nation-wide/UK	Pipeline	Consider uncertainties in the storage capacity and the financial market in the model
(Nie et al., 2017)	Total cost minimization	MILP	Nation-wide/UK	Pipeline	
(Klokk et al., 2010)	Net present value maximization	MILP	Nation-wide/Norway	Pipeline	
(Kalyanarengan Ravi et al., 2017)	Total cost minimization	MILP	Nation-wide/Netherlands	Pipeline	
(Ağralı et al., 2018)	Net present cost minimization	MILP	Nation-wide/Turkey	Pipeline	Consider only fossil-fired power plants as CO_2 sources
(Leonzio et al., 2019)	Total cost minimization	MILP	Nation-wide/Germany	Pipeline	
(Becattini et	Multi-	MILP	Nation-	Ship,	

al., 2022)	objective: Total cost minimization and emission minimization		wide/Switzerland	Pipeline, Barge, Truck, Rail	
(Turk et al., 1987)	Profit maximization	MILP	Region-wide/Ohio	Pipeline	
(Middleton et al., 2012)	Total cost minimization	MILP	Region-wide/Texas	Pipeline	
(Middleton & Bielicki, 2009b)	Total cost minimization	MILP	Region-wide/California	Pipeline	
(Yue et al., 2015)	Multi-objective: Total cost minimization and GHG emissions avoided maximization	MINLP	Region-wide/Texas	Pipeline	
(J.-H. Han & Lee, 2012)	Profit maximization	MILP	Region-wide/Pohang	Truck, Ship, Pipeline	
(S.-Y. Lee et al., 2017)	Multi-objective: minimize the combination of (1) cost, (2) environmental impact, and (3) risk due to uncertainties	MILP	Region-wide/Pohang	Truck, Ship, Pipeline	
(Zhang et al., 2020)	Net cost optimization	MILP	Region-wide/Northeast	Pipeline	

			China		
This paper	Multi-objective: Minimize the total system cost and maximize the amount of avoided CO_2	MILP	Nation-wide/Norway	Pipeline, Ship, Truck	Consider a wide range of sectors as CO_2 sources (cement, iron & steel, refinery, petrochemical, aluminium, silicon, fertilizer, and natural gas processing

Table 2.2. An indicative list of research on the optimization of CCS supply chain networks

2.3.4. *Key takeaways*

Several papers studied the end-to-end planning and design of the supply chain for CCS with common objective functions as total cost minimization or net cost minimization. Net costs represent the difference between the total costs and the benefits gained from CO_2 emission reduction efforts. A few papers also deployed multi-objective optimization model to systematically assess the trade-offs between environmental regulations and economic value (Federico d'Amore et al., 2020; Becattini et al., 2022; Yue et al., 2015; S.-Y. Lee et al., 2017).

In the optimization model, most of the papers include the regulation on CO_2 emissions as a constraint. Also, the decisions need to be made include the selection, size and location of CO_2 capture and transport networks, CO_2 capture processes and technologies, CO_2 source-sink mapping, CO_2 flow between sources and sinks, selection of storage sites, the amount of CO_2 stored and energy expenditure for CO_2 transport. (Hasan et al., 2022)

In terms of transport infrastructure, pipeline is the most economical way for transporting large volumes of CO_2. Recently, ship and barge have been proved to be competitive with offshore pipelines in some cases. Meanwhile, truck and rail should only be used when taking into account shortsighted time horizons or small volumes of CO_2 transported.

Finally, a majority of the papers exploited MILP for optimizing CCS supply chain networks through deploying linear relaxations for cost expressions or nonlinear process dynamics.

3. Research methodology

Research methodology concerns an entire process through which a study goes to answer the research questions. Also, the choice of research methodology has a significant impact on the finding of the research. In this chapter, we will clarify the methodological approach selected to solve our research question. First, we will go through research strategy and research design. Then, how data was collected and analyzed will be described and later, we will highlight the quality assessment of the thesis.

3.1. Research strategy

A proper selection of research strategy plays a critical role in achieving research objectives (Ragab & Arisha, 2018). Research strategy refers to a general direction researchers go to collect and analyze information to answer their research questions (Bryman et al., 2019; M. Saunders et al., 2016). Business research generally differentiates between a quantitative and qualitative research strategy. The quantitative method is mainly based on the collection of quantification and numerical data, while the qualitative method is based more on words in the data collection and analysis steps (Bryman et al., 2019).

In addition, in terms of operation management research, Karlsson (2008) pointed out that model-based quantitative method has become the basis of most of the studies. The model-based quantitative method replies on a group of variables which vary over a particular domain, while casual and quantitative relationships have been established among these variables. Will M. Bertrand & Fransoo (2002) classified model-based quantitative method into two different classes: axiomatic and empirical research. The main concern of the axiomatic research is to obtain solutions that can provide insights about the structure of the real-life problem as designed under the model, while that of empirical research is to find a model that can explain the real-life problem. Moreover, empirical research requires researchers to acquire more knowledge about the characteristics of the problem under study than axiomatic research. (Will M. Bertrand & Fransoo, 2002)

Owing to the unavailability of large-scale minimum-cost CCS networks, especially under the Norwegian context, axiomatic model-based quantitative method has been chosen for this study to find an optimal CCS supply chain. Besides, it is deemed essential to gather both quantitative and qualitative data to answer the research question. Therefore, this paper will exploit a combination between model-based quantitative and qualitative methods but is more inclined to the former. Another vital aspect of combining these two strategies is the desire to employ the logic of triangulation since it allows cross-checking between findings from both quantitative and qualitative data (Deacon et al., 1998).

The qualitative method will be applied in selecting, synthesizing, and summarizing related articles, studies, and internal documents. Moreover, qualitative research will be employed to analyze data from interviews with professional researchers. The qualitative data was then further utilized to establish overview context and insights for the quantitative data. The model-based quantitative method will be implemented, as suggested by Mitroff et al. (1974), cited in Will M. Bertrand & Fransoo (2002) (Figure 3.1), to determine a cost-optimal supply chain network for CO_2 capture, transportation, and storage while meeting different emissions targets. Firstly, we chose a conceptual model by identifying the scope, objectives, and decision variables of the problem. Then, a quantitative model was built through defining causal and quantitative relationships among variables. After that, the model was solved and finally, the result of the model is presented and analyzed prior to the beginning of a new cycle.

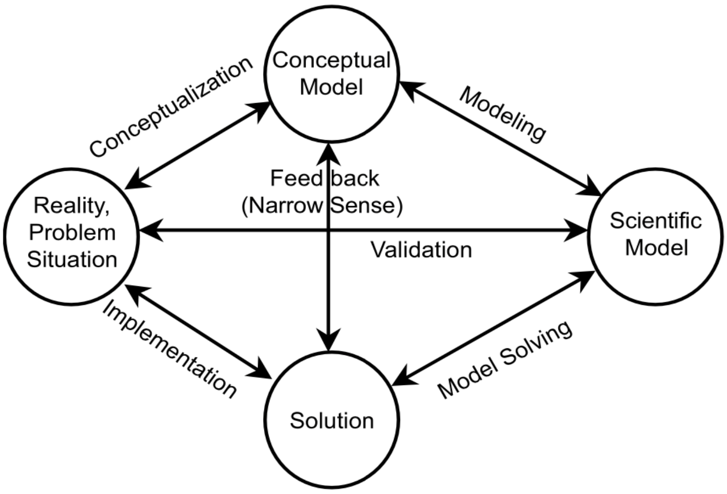


Figure 3.1. Model-based quantitative research (*Mitroff et al. (1974) cited in Will M. Bertrand & Fransoo (2002)*

When it comes to the research structure, there are three approaches, namely inductive, deductive, and abductive. An inductive approach is characterized as theory being data-driven; in other words, the inductive approach enables theory to arise from research. A deductive approach is implemented to test hypotheses driven from earlier theory. As a combination of the two above approaches, an abductive approach starts with recognizing a phenomenon and then seek to answer it by investigating iteratively between theory and practice. (Bryman et al., 2019)

For this thesis, the abductive approach is selected rather than a strict logic of theory-testing (deduction) or theory-building (induction). Dubois & Gadde (2002) believe that the abductive approach is a better choice for researchers to connect theory and practice. This is more crucial when the literature on the topic of this study is limited, especially under the Norwegian context. The abductive approach enables us to move back-and-forth between literature and observation to create a research question and collect necessary data before coming up with meaningful findings. A demonstration of the abductive approach used in this study is shown in Figure 3.2.

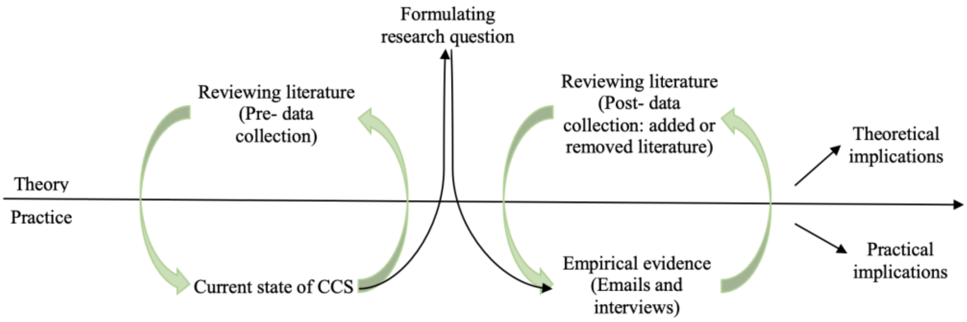


Figure 3.2. Abductive approach *(synthesized by authors)*

3.2. Research design

According to R. Kumar (2018), research design serves as a roadmap guiding researchers to answer the research question with the utmost objectivity, accuracy, validity, and cost-efficiency. In line with that, Bryman et al., (2019) define research design as a framework assisting researchers in gathering and analyzing data to address the research question. There are various types of research design, namely cross-sectional design, case study design, comparative design, experimental design, and longitudinal design (Bryman et al., 2019).

In this thesis, we will design a case study in Norway to answer the research question. As stated by Dul & Hak (2007), a case study is appropriate when the current theoretical framework insufficiently address the empirical phenomena in a comprehensive manner. According to Bryman et al., (2019), a case study is most relevant for investigating a bounded situation or system intensively. Norway is one of the world's pioneers in the development of full-scale CCS projects. However, these projects involve single chains instead of a widespread network of different CO_2 sources, transport modes and storage locations. From the supply chain perspective, we want to study how a minimum-cost supply chain network for CCS can be designed to satisfy different goals of reducing emissions. This case study design is suitable as although there has been research on SCND for CCS in some countries or areas, studies on this topic in Norway has not been thoroughly investigated.

There are several types of case studies that possess different characteristics. Stake (1995), cited in Bryman et al. (2019), differentiates between three types of case studies: instrumental, intrinsic and multiple or collective. Instrumental case studies serve as a mean to comprehend broader issues or challenge generalizations. Intrinsic case studies, on the other hand, are appropriate for comprehending the unique aspects of a situation rather than seeking generic understanding. Finally, multiple or collective case studies are employed to gain insight into a general phenomenon by connecting multiple studies. In our research, we aim to design a CCS supply chain network specifically in Norway. At the same time, the model we built exhibits flexibility and generality, making it applicable to various geographic locations. Through designing a network at a country level, we can also evaluate the feasibility of clustering small-scale emission sources generally. Thus, we deem our study as a combination of intrinsic and instrumental case studies.

It is critical for researchers using a case study approach to establish a clear understanding of the level of analysis to be undertaken (Bryman et al., 2019). In simpler terms, researchers need to determine the unit of measurement and analysis for their study. The level of analysis might revolve around individuals, groups, organizations and societies (Bryman et al., 2019). In order to obtain a deeper understanding and data about CCS in Norway, we adopted an organizational level of analysis. We justified this choice by considering that while we conduct interviews with individuals, their responses are considered representative of their respective organizations.

3.2.1. Sampling

This section will elucidate the sampling method for the interview and the process of choosing interviewees. According to Bryman et al. (2019), it is common in a case study that the selection of samples is based on their suitability for the objectives of the investigation. This is known as purposive or non-probability sampling, in which participants are selected strategically based on their relevance to the research question, rather than randomly (Bryman et al., 2019). The sample members should have different characteristics relevant to the problem statement to ensure the variety of the resulting sample. For our research, it is crucial that participants meet specific criteria, such as knowledge about CCS and SCND for CCS. Therefore, purposive sampling is the most suitable approach for our research.

We identified two fundamental criteria for our interviewees: (i) CCS knowledge (technical and industry knowledge) and (ii) expertise in SCND for CCS (our focus topic). Based on these criteria, we identified three target groups of participants that are relevant to our research question: (1) technical experts in each component of CCS, namely CO_2 capture, CO_2 transport and CO_2 storage, in Norway; (2) experts in CCS market in Norway and (3) experts in SCND for CCS at different scales. We aimed to have 2 to 3 interviews for each group, amounting to a total target of at least 6 interviews.

We utilized various methods, including cold calls via email, getting contact from CLIMIT Summit 2023 organized in Norway, and leveraging our supervisor's networks, to identify interview candidates who belong to one of the three target groups. Furthermore, to expand our search and reach out to suitable potential interviewees, we employed a snowballing approach. As stated by Bryman et al. (2019), this method involves leveraging initial contact with a small group of individuals relevant to the research to establish connections with others. During the interview, we inquired with participants about other relevant stakeholders who might be of interest to the research project to contact them later.

As of May 2023, we reached out to 16 potential participants. Initially, they were contacted via email, which included a brief introduction of the interviewers, an overview of the study and the reason why we invited them to participate. In instances where we did not get an answer, follow-ups were made through email. Eventually, we achieved a success rate of nearly 44% with 7 participants from different organizations and 9 interviews in total, in which we conducted 3 interviews with a senior specialist of Norwegian Geotechnical Institute (NGI) as this is our main partner in the thesis project. The list of interviews, the interviewees' organization as well as the group they are in are presented in Table 3.1.

Date	Target group	Organization	Location	Length (mins)
17.11.2022	2	NGI	NGI	60
29.12.2022	2	NGI	Zoom	60
10.02.2023	1	Gassnova	Zoom	15
13.02.2023	1	The Research Council of Norway	Zoom	15
14.02.2023	1	Sintef	Zoom	60
23.02.2023	3	University of Padova, Italy	Microsoft Teams	60
28.02.2023	3	ETH Zürich, Switzerland	Zoom	60
03.05.2023	2	NGI	Zoom	60
26.04.2023	1	Hafslund Oslo Celsio	Zoom	30

Table 3.1. List of interviews

3.3. Data collection

Data collection is a crucial point of any research (Bryman et al., 2019). The literature separate types of data into secondary data and primary data. According to M. Saunders et al., (2016), secondary data is defined as information that has been generated for other sources. Primary data is information collected by researchers for the aim of the research (Bryman et al., 2019). In other words, primary data is observed or gathered from first-hand experience.

3.3.1. Secondary data

Owing to the time-consuming process of collecting primary data, secondary data is essential to gain insights into the topic. In this research, secondary data is obtained from existing literature, such as previous and relevant articles, research and reports on the topic, and websites of some related organizations. This data helps us to grasp the knowledge of each component in CCS supply chain, derive inputs for the optimization model as well as understand tools and methods for evaluating total costs and environmental impacts of the CCS supply chain network. As the abductive approach is chosen, we need to go back-and-forth between observations and research. Thus, the literature was regularly added and removed.

3.3.1.1. Literature

At the beginning of the data gathering process, existing literature was reviewed. To get relevant papers and comprehensively interpret related concepts and models, we searched through some online sources. The search was conducted by applying search strings, narrowing down the amount of literature and ensuring that relevant papers are not excluded. These search strings are based on a distinctive combination of the following keywords which are relevant with the research question: supply chain, network design, CCS, cost, technology, carbon/CO_2 capture, carbon/CO_2 transport/transportation, carbon/CO_2 storage, challenges, barriers, difficulties, opportunities, energy consumption, etc.

The main platforms we have accessed are Oria and Google Scholar. To acquire an extensive database, we also accessed some well-known journals in logistics and supply chain management, namely International Journal of Supply Chain Management or International Journal of Operations & Production Management. In addition, the International Journal of Greenhouse Gas Control, focusing mainly on carbon capture, transport, utilization, and storage, was also considered to gain a deep understanding about the topic. Reviewing previous literature provides an in-depth background, enabling us to build up a well-prepared interview guide.

3.3.1.2. Websites

Another important source to obtain suitable secondary data is websites of related organizations. Through Google, we identified some websites of crucial and relevant organizations, including (1) international organizations, such as Global CCS Institute, and IEA; (2) Norwegian companies and platforms, namely Norske Utslipp (Norwegian PRTR), Northern Lights, Technology Centre Mongstad, SINTEF, GASSNOVA, and CCS Norway.

a. International organizations

- **Global CCS Institute**

Global CCS Institute is “an international think tank whose mission is to accelerate the development of carbon capture and storage” (Global CCS Institute, n.d.). The institute’s main activities are to share expertise, build capacity and provide advice and support in the development of CCS. The institute also provides a rich database in CCS facilities and global status of CCS, enabling us to obtain crucial numbers about CO_2 capture process.

- **IEA**

Established in 1974, the International Energy Agency (IEA) has been working with governments and industries to maintain a secure and sustainable energy future for all countries (IEA, n.d.). IEA provides authoritative data, analysis, real-world solutions, and policy recommendations to make better decisions (IEA, n.d.). Moreover, IEA also offers some databases on CCS. By cultivating this database, the author extracted consistent insights about capturing CO_2 emissions.

b. Norwegian companies and platforms

- **Norske Utslipp (Norwegian PRTR)**

The Norwegian PRTR website presents information about annual emissions released to air and water as well as waste transfers from different companies in Norway who have obligations to report emissions to the Norwegian Environment Agency (Miljødirektoratet) and the State Administration (Statsforvalteren) (Norske Utslipp, n.d.). The website consists of data of both point sources and emissions amount. From this website, the volume of emissions of each Norwegian CO_2 source was retrieved.

- **Northern Lights**

Northern Lights was established in March 2021 as a partnership among Equinor, Shell and TotalEnergies (Northern Lights, n.d.-c). Northern Lights has responsibility for developing and operating carbon transport and storage facilities for the Norwegian government's full-scale CO_2 capture and storage project (Northern Lights, n.d.-a). Through the website of Northern Lights, we understand more about the features of storage site as well as the CO_2 storage process.

- **Technology Centre Mongstad**

Technology Centre Mongstad (TCM) is owned by the Norwegian State and operated by Equinor (Technology Centre Mongstad, n.d.). The main purpose of TCM is testing, verifying and demonstrating different and cost-efficient technologies for capturing CO_2. TCM is also considered as the world's leading and largest center for developing CO_2 capture technologies. As a result, this source provides interesting information about CO_2 capture technologies.

- **SINTEF**

SINTEF was found in 1950 by the former Norwegian Institute of Technology (SINTEF, n.d.). Due to its growth as well as mergers with other institutes, SINTEF has become one of Europe’s largest independent research organizations. Every year, SINTEF carries out thousands of projects which cover a wide range of topics. Among those topics, CCS is also an important area SINTEF focuses on. By diving into SINTEF’s published research on CCS, we gained some necessary data about the CO_2 capture and transportation processes.

- **GASSNOVA**

With the purpose of promoting development of technology for cost effective solutions for CCS, Gassnova was created by the Norwegian state in 2005 (GASSNOVA, n.d.). On behalf of the state, Gassnova has been closely engaged in the management of the first full-scale CCS project in Norway, the Longship project. Additionally, with the aim of sharing knowledge on CCS, the company is responsible for managing a funding scheme for technology development for CCS, namely CLIMIT program. From this program, a considerable number of contacts of related researchers on CCS in Norway were found.

- **CCS Norway**

CCS Norway, developed by GASSNOVA, serves as a specialized platform with the objective of boosting and assisting the progress of CCS technologies and projects in Norway. CCS Norway acts as a central focal point for staying updated on the most recent news, research, and advancements of the Longship project in Norway. Thus, it fosters knowledge sharing and promotes collaborative efforts among researchers, policymakers, industry experts, and stakeholders involved in CCS.

3.3.2. Primary data

Primary data refers to the data that researchers collect for their research objectives (Bryman et al., 2019). Primary data plays a vital role in obtaining the findings of this thesis since secondary data alone are inadequate to address our research question. In our thesis, we collect primary data from interviews with representatives of relevant organizations. Through those interviews, we not only gain in-depth qualitative insights into CCS situation in Norway but also are able to assess if quantitative data collected from literature and public sources can be applied in the Norwegian context. Furthermore, we can also get clarifications on each component of the optimization model and methods to run the model efficiently.

As we want to guide interviewees through uniform questions and remain adaptable to their responses, semi-structured interviews are employed to add flexibility from different flows of the conversations to the standardization of an interview guide. According to (Bryman et al., 2019), an interview guide contains lists of questions related to specific topics that need answering. This approach enables researchers to explore interesting aspects that arise during the interview and allows for additional probing and follow-up on those topics.

To solve the research question, we developed a customized interview guide for each of the three target groups using literature review and secondary data, as attached in Appendix 1. In the first target group which includes experts in each component of CCS in Norway, we further broke the guide down into three parts, namely CO_2 capture, CO_2 transport and CO_2 storage so that we can ask the right questions to the right person. Customizing the interview guide helps us to maximize the richness and depth of the data gathered from each group of interviewees. Additionally, we conducted pilot interviews prior to the actual interviews with a view to familiarizing ourselves with the interview setup, as well as uncovering any questions that are potentially problematic (Bryman et al., 2019). As a result of the pilot phase, certain questions were adjusted. Besides, we gained valuable insights from piloting the interview process, such as the need to allocate time for open discussions in the end and notice our body language throughout the interviews.

The interviews are held both online and offline, but mainly online through Zoom or Team platform due to either the geographical distance or busy schedule of interviewees. All interviews were carried out in English and lasted from 15 minutes to 1 hour. Some instructions from Saunders et al. (2019) are followed to address quality problems of semi-structured interviews. At the beginning of the interviews, we provided an introduction about ourselves, our study, and its purpose to ensure clarity for the interviewees. To better contextualize interviewee's responses, we ask them about their positions and their working experience (Bryman et al., 2019). Subsequently, we followed the questions outlined in the interview guide while remaining adaptable to the flow of conversation. Throughout the interviews, we made use of note-taking, which allowed us to ask follow-up questions and served as a back-up for recording the data (M. N. K. Saunders et al., 2019). Finally, immediately after each interview, we dedicated time to writing comprehensive notes, ensuring that we captured our immediate impressions and important information from the answers.

3.4. Data analysis

After collecting data, the subsequent stage involves transforming it into valuable information through analysis. In essence, the process of data analysis is primarily about reducing the vast pool of data collected into a meaningful and actionable form that can be utilized to generate value (Bryman et al., 2019). In this thesis, we obtained different data types that necessitated the utilization of different analysis methods. Thus, this section will be segregated into two parts to address our qualitative and quantitative data analysis separately.

3.4.1. Qualitative data analysis

Regarding the qualitative data, the analysis needs to be performed to provide a thorough picture of each CCS component in Norway. This analysis ensures that the input data used in our model is relevant and reflects the Norwegian context. To carry out the analysis, we followed two crucial steps, namely data preparation and template analysis (M. N. K. Saunders et al., 2019).

For data preparation, we wrote notes during and immediately after each interview to capture information from the answers. We employed certain functions in MS Word such as bold, underline and italic to highlight parts that we should pay the most attention to. Furthermore, maintaining quality assurance is a fundamental aspect of the research process. To achieve this, we compared the notes between both of us multiple times. The objective was to ensure the accurate representation of the interviewees' statements, avoiding any misquotations or misinterpretations that could potentially distort the data or remove its contextual relevance.

The next step is template analysis. According to Saunders et al. (2019), both inductive and deductive approaches can be combined within template analysis by initially predetermining categories and later modifying or expanding them as data is collected and analyzed. This process consists of two steps: first, developing templates, and then associating relevant data with these templates. Thus, we had established a template that includes categories corresponding to each component of CCS and their sub-categories. Subsequently, we organized data from our notes into this template. By doing template analysis, we could dissect the vast number of notes into different categories, which allows us to filter relevant details easily and identify similarities and differences in participants' viewpoints on the given topic. Based on this, we could map the CCS system in Norway and proceed with our model.

3.4.2. Quantitative data analysis

In our study, the quantitative data was retrieved from various sources, including literature, websites, documents from relevant organizations, and interviews. To begin, we transferred this data to Excel for cleaning and processing. Understanding the structure and content of the data is crucial in order to carry out effective data cleaning. Thus, descriptive statistics were conducted using the "Data Analysis" ToolPak, an Excel add-in, to get an overview of data. Then, we cleaned the data by ensuring correct data types and eliminating any duplicate, missing or unwanted values. Furthermore, for cost data, we put them to a common economic basis ($€_{2020}$) using the chemical engineering plant cost index and exchange rate collected from reliable websites. When it comes to distance data, we converted all measurements to kilometers (km) to ensure consistency. Similarly, emissions data were standardized to metric tonnes. These steps make sure that the units of data input are consistent, laying a firm foundation for the model to run properly.

After making the necessary modifications to the data file, we proceeded with the subsequent steps. We utilized different features, formulas and functions in Excel to analyze the data. For example, when working with emissions data, we employed sorting and filtering features to select the twenty largest CO_2 sources and arrange them in descending order. Graphs were also used to visualize the distribution of emissions across various sectors. Furthermore, we employed pivot tables to group the emissions by regions, providing a basis for choosing port candidates for ship transport. Excel is also the software that we utilized to build up our mathematical optimization model, which includes objective functions, decision variables and constraints, due to its familiar interface and easy use. After running the model for various scenarios, we continued to analyze, visualize and interpret the results to get meaningful findings and insights.

3.5. Quality of the research

Regarding quantitative research, three primary criteria to evaluate the quality of the research are reliability, validity, and replicability. In business research, however, replicability is not common (Bryman et al., 2019). When it comes to qualitative research, there are two criteria to assess the quality, namely trustworthiness and authenticity (Bryman et al., 2019; Lincoln and Guba,1985; Haldorsson and Aastrup 2003). Trustworthiness consists of four dimensions, including credibility (paralleling with internal validity in quantitative research), transferability (paralleling with external validity), dependability (paralleling with reliability), and confirmability (Bryman et al., 2019). As our study applies both quantitative and qualitative research, we will evaluate the quality of the research in terms of reliability, validity, confirmability and authenticity.

3.5.1. Reliability

Reliability refers to whether the study’s findings are consistent over time. In other words, reliability pertains to the stability of results when a study is conducted on separate occurrences (Bryman et al., 2019). To achieve reliability, researchers should provide a clear and transparent account of the research process from the initial stages of the research to the reporting of the results. Hence, it is important to maintain records of the research in an organized and accessible manner throughout the study. (Guba & Lincoln, 1994)

In order to ensure reliability, we established a unified database for the thesis. A designated folder on Office 365 OneDrive was created as a central platform to store all relevant documents, enabling us to utilize them as supporting evidence. This folder encompasses various documents from the early stages of the research, including problem formulation, the projects’ timeline, selection of interviewees and the interview guide. After each interview, the interview notes are also processed and kept there. Additionally, it contains copies of all articles and documents from relevant organizations that our quantitative data is collected from. Moreover, the database includes our full mathematical model, results of the model and our analyses. These measures guarantee that other researchers have access to data, follow the same procedures as undertaken in this research and get the same results, thereby ensuring reliability.

3.5.2. Validity

Another prominent criterion for evaluating research is validity. Validity deals with the accuracy of studies. In other words, validity concerns the integrity of conclusions generated from research. Validity includes internal validity and external validity. Internal validity requires that research has established a genuine cause-and-effect relationship that is not able to be explained by other factors. External validity concerns whether findings can be applied to other contexts or the extent to which findings can be generalized. (Bryman et al., 2019)

3.5.2.1. Internal validity

In this research, internal validity depends significantly on the ability of the writers to identify relevant variables affecting CCS supply chain network design and ultimately build an appropriate model. To ensure the internal validity, we applied triangulation and respondent validation techniques as suggested by Guba and Lincoln (1994), cited in Bryman et al. (2019).

Triangulation is the technique using multiple methods or sources of data to investigate one phenomenon, which leads to a greater assurance of finding. In this study, we reviewed many previous papers in designing CCS supply chain network to gain a thorough overview of the problem. Additionally, to determine proper variable influencing CCS network design, data for each aspect of CCS has been extracted from at least two different existing studies. Furthermore, data from the interviews has been used to verify and confirm the collected secondary data. Concerning respondent validation technique, the meaning of this method is checking research with other researchers in the field. When the model was completely built, we presented it to experts in CCS and SCND for CCS to ensure that the collected data was interpreted correctly and that the model is relevant.

3.5.2.2. External validity

When examining external validity, the issue of how people are chosen to take part in research becomes more essential (Bryman et al., 2019). In this study, although the primary data was collected from a small group of participants, the relevance of the participants is high as they all are specialists in CCS or SCND for CCS. Furthermore, while the finding of this study is more inclined to the Norwegian context, the model is designed such that it can be applicable to various sectors, transport systems and geographic regions. Therefore, provided that some data under the Norwegian context, such as CO_2 sources, electricity carbon intensity or cost data, is adjusted, this model can be transferable to other contexts.

3.5.3. Confirmability

Confirmability concerns the assurance that, even though absolute objectivity is unattainable in business research, the researchers can show their sincere intentions during the research period. In other words, confirmability does not allow excessive or noticeable personal beliefs or theoretical preferences to influence the research process and its resulting conclusions (Bryman et al., 2019). We implemented some measures to ensure confirmability throughout every stage of the research process. First, we made sure that both of us were present in every interview conducted. In fact, our supervisor also attended most interviews. Second, we regularly sought consultations from our supervisor and the senior specialist of NGI during the period conducting this study. Furthermore, we support all the findings by reliable data and results from running the optimization model. By doing so, all the conclusions and recommendations can be traced back to their sources easily and thus eliminate any doubts about subjectivity.

3.5.4. Authenticity

Authenticity is related to *"the wider social and political impact of research"* (Bryman et al., 2019, p. 365). By designing a CCS supply chain network that is cost-effective and contributes to decarbonization, our research benefits multiple stakeholders. First, it provides industries and businesses with valuable insights into how CCS network can reduce their carbon emissions effectively and thus help them to meet their sustainability objectives and comply with regulations. Second, the research can assist policy makers and regulators in decision-making processes, enabling the formulation of guidelines that facilitate the establishment and operation of CCS supply chains. When it comes to investors, the research helps them to understand the economic viability and financial feasibility of different supply chain configurations. Moreover, this research contributes to advancing the implementation of a robust and interconnected CCS network which ultimately helps to reduce GHG and benefit the society as a whole.

3.6. Ethical and societal consideration

When conducting research, it is essential for researchers to be aware of ethics in their research projects. Many ethical issues may emerge during the process, and it is critical to manage them adequately. Bryman et al. (2019) indicate that there are four main categories of ethical issues which must be handled in the research, including participant harm, informed consent, privacy invasion and deception. Participant harm pertains to safeguarding all participants of the research from any kind of harm, both directly and indirectly. Informed consent concerns that respondents of the study must be fully informed of the research. Invasion of privacy highlights the rights of participants to decline providing personal or sensitive information during interviews or in response to certain questions. Deception ensures that researchers will avoid all cases in which respondents are empowered to answer questions in a biased way or less naturally.

This study was conducted with all those four ethical considerations in mind. The purpose of the research was explained thoroughly to all participants at the beginning of every email and before the interviews. Moreover, the participants were anonymized by providing them with identifier codes. Also, participants have the right to withdraw from the research without any further explanation. Additionally, the interview guides have been created under thorough examination, making sure not to ask personal data or not enabling biased responses to meet the two last ethical considerations.

4. Optimization model for SCND for CCS

In this section, we will elaborate on the modelling framework and methods used to design the optimal CCS supply chain network. Subsequently, the system in Norway in terms of each component of CCS and inputs for the model are described. Finally, mathematical optimization model is formulated and explained.

4.1. Modelling method

The supply chain network of CCS includes three sequencing stages: capture, then transport and finally storage. Instead of focusing on only an individual unit in the network, our model displays a holistic view through identifying an optimal network for the entire CCS supply chain. Accordingly, the model answers the following questions simultaneously: which sources will be selected, how much CO_2 will be captured at the sources and stored at storage sites, which transport modes will be implemented and how much CO_2 will be transported between two nodes.

In other words, the model presents two kinds of decision variables: (1) investment decisions concerning whether to install capture units at sources or transport modes between two nodes are illustrated by binary variables, which can only take 1 or 0 values; (2) operational decisions refer to amount of CO_2 captured, transported, or stored and are illustrated by continuous variables as they can take any non-negative values satisfying certain constraints. Furthermore, the solution of the model must satisfy all constraints which are formulated under linear functions. The objectives of the model are minimizing the total system cost and maximizing the total CO_2 amount avoided. These objective functions are also linear. It is also worth noting that we do not consider any time-dependent factors in our model. As a result, the model obtained is a multi-objective, multi-stage, multi-echelon, and static mixed integer linear programming (MILP) model.

Although there are many methods usable to solve multi-objective model, the ε-constraint approach is chosen for this study as it allows to depict the trade-off between minimizing the system cost and maximizing the CO_2 avoidance level through a Pareto curve. In the general form, a multi-objective MILP model using the ε-constraint method can be written as follows:

$$\min_{x,y}(ax+by) \text{ subject to } \begin{cases} cx+dy \geq \varepsilon \\ Ax+By=e \\ x \geq 0 \\ y \in (0,1) \end{cases}$$

where a, b, c and d are vectors expressing the objective functions of the model in relation to continuous decision variable, x, and binary decision variable, y. ε is the upper or lower bound for one objective function. A and B are the constraint matrices corresponding to variable x and y and e is a vector representing the constant value of the constraints.

Despite the inherent difficulty of solving MILP problems compared to linear programming (LP) problems, there exist numerous commercial and non-commercial software packages specifically developed to address MILP problems. Commercial packages may include CPLEX, Gurobi, LINDO and MOSEK while some noticeable non-commercial packages are BLIS, CBC, GLPK, MINTO, SCIP and SYMPHONY (P. H. Kumar & Mageshvaran, 2020). In general, non-commercial MILP software packages are unable to achieve the same level of speed and reliability as their commercial counterparts.

In this thesis, we chose to use Gurobi 10.0.1 to solve the MILP problem of CCS supply chain optimization. Fortunately, as students using Gurobi Optimizer for academic use, we can get free licenses while benefitting from the same solving power as commercial licenses (Gurobi, n.d.-a). There are several reasons why we selected Gurobi optimizer for our project. First, it is known as the world's fastest solver (Gurobi, n.d.-b). Public benchmarks consistently demonstrate that Gurobi outperforms competing solvers by finding solutions that are feasible and proven optimal at a faster pace. Second, Gurobi incorporates cutting-edge techniques exclusively tailored for MILP problems. These include methods such as primal heuristics, symmetry detection, and cutting planes, which help to not only reduce solution time but also enhance solution quality. Furthermore, continuous development and strong support ensure users have access to the latest advancements and assistance in leveraging Gurobi's capabilities effectively. (Gurobi, n.d.-b)

Another advantage of Gurobi is that users can easily incorporate its optimization capabilities into their preferred development environments and leverage its advanced features and performance to solve complex problems (Gurobi, n.d.-b). In our thesis project, we integrated Gurobi with OpenSolver which is an open-source optimization modeling and solving tool primarily built as an Excel add-in (OpenSolver, n.d.). Accordingly, we only need to define decision variables, constraints and objective functions within the familiar Excel environment provided by OpenSolver. Then, OpenSolver will communicate with Gurobi solver to find optimal or near-optimal solutions for the defined problem. This strategy not only simplifies the process of formulating the optimization framework but also makes our model accessible to people with limited knowledge of programming or modelling languages.

To solve such a complex problem as SCND for CCS in Norway, we decided to utilize a mixed integer programming (MIP) gap of 1%, which means that the solver will terminate when the best feasible solution found is within 1% of the optimal solution (Gurobi, n.d.-c). This MIP gap of 1% is also employed by Becattini et al. (2022) when solving the optimization problem of the CCS supply chain network in Switzerland. We chose this threshold as it strikes a balance between solution quality and computational resources. It allows for finding reasonably good solutions without excessive computational time, especially for our problem where finding the exact optimal solution is very challenging and may be computationally infeasible.

4.2. System description and model inputs

This research introduces a MILP modeling framework which aims to optimize a CCS supply chain in Norway in terms of costs and avoided CO_2 with a focus on major industrial CO_2 sources including refinery, petrochemical, cement, iron & steel, aluminium, silicon, natural gas processing, and fertilizer. The model covers all components of CCS from capture units tailored for different sectors, transport through a multi-modal network including pipelines, ships and trucks and storage in suitable offshore geological reservoirs, as illustrated in Figure 4.1. and Figure 4.2. The spatially explicit characteristics of the system are demonstrated through a set of nodes denoted as N. The subset of N includes N^c indicating the location of CO_2 emission sources, N^s indicating the location of storage sites and N^h indicating harbors across Norway for CO_2 ship transport.

Specifically, N^c further includes:

n = $r_{1\text{-}2}$, corresponding to 1 refinery node and 1 petrochemical plant node;
n = {$c_{1\text{-}2}$}, corresponding to 2 nodes of cement factories;
n = {$i_{1\text{-}4}$}, corresponding to 4 nodes of iron or steel plants;
n = {$s_{1\text{-}5}$}, corresponding to 5 nodes of silicon plants;
n = {$a_{1\text{-}5}$}, corresponding to 5 nodes of aluminium plants. We further define the set of steps in aluminium plants as P, and P includes p = refining and p = smelting;
n = {$o_{1\text{-}2}$}, corresponding to nodes of other industries including production of

fertilizers and natural gas processing.

Meanwhile, N^s includes:

n = {$m_{1\text{-}3}$}, corresponding to 3 storage nodes, namely Northern Lights, Smeaheia and LUNA.

N^h includes:

n = {$h_{1\text{-}7}$}, corresponding to 7 harbor candidates in Norway for CO_2 ship transport, namely Port of Narvik, Port of Mosjøen, Port of Porsgrunn, Port of Kårstø, Port of Årdalstangen, Port of Sunndalsøra and Port of Husnes.

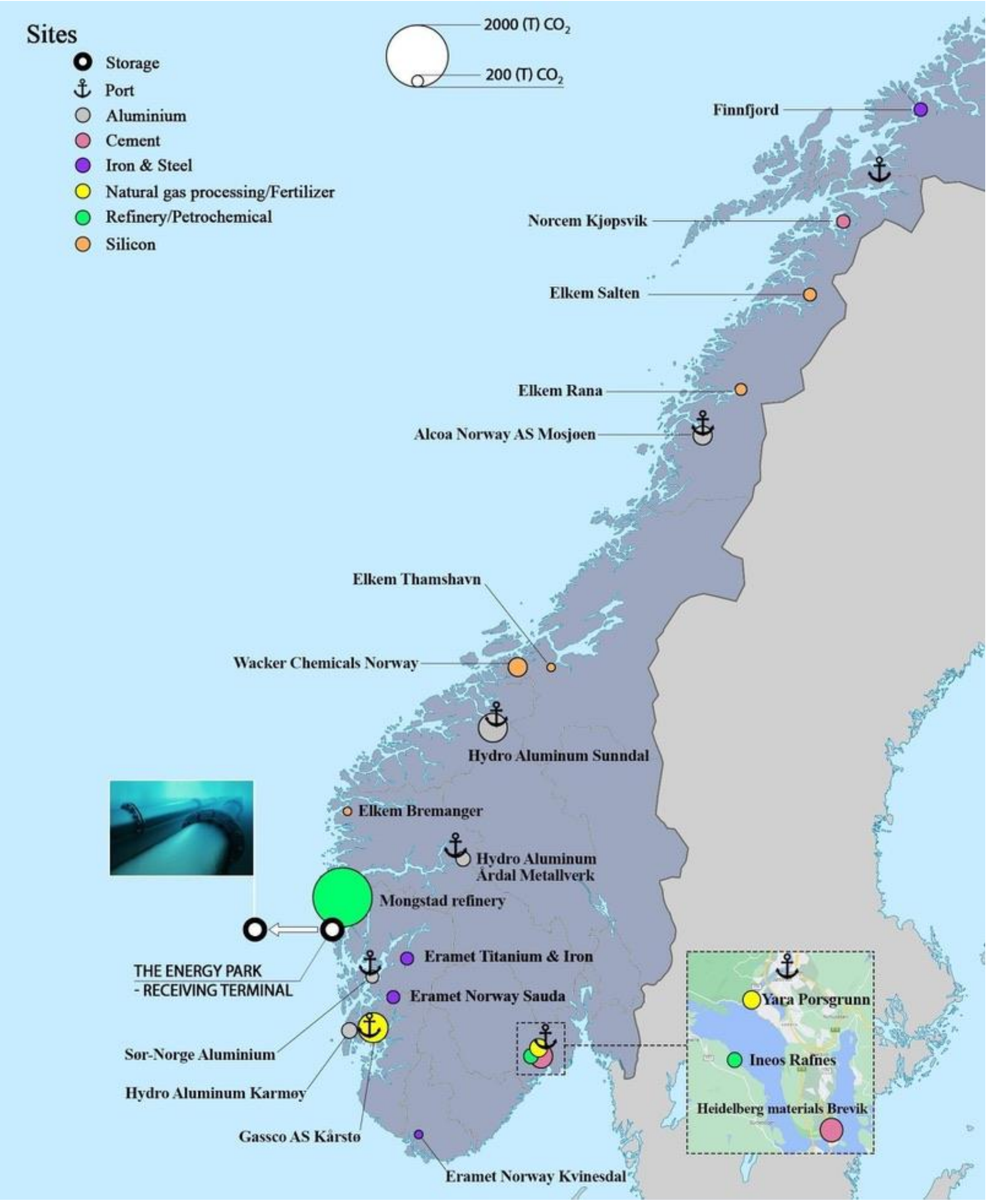


Figure 4.1. Illustration of the system setup

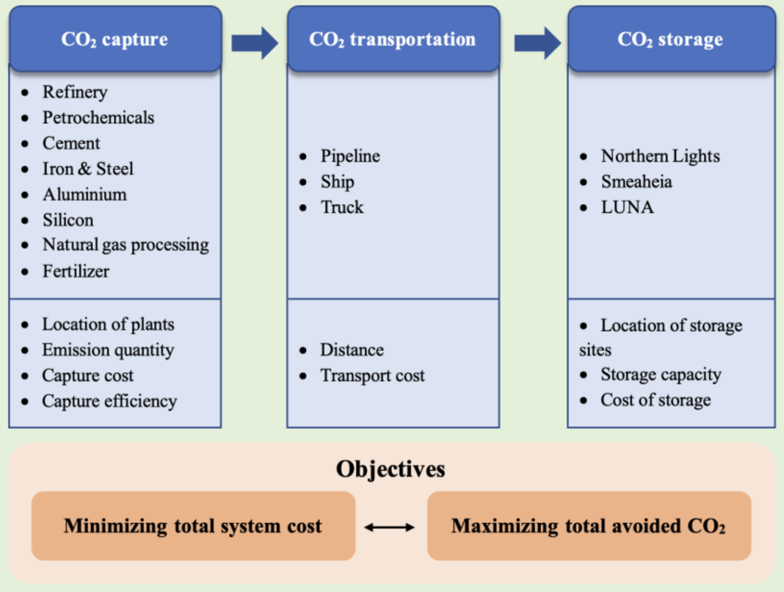


Figure 4.2. CCS supply chain network model in this study

4.2.1. Emission sources

In Norway, a significant part of the anthropogenic CO_2 emissions originates from industry which is the focus of this study (Statistics Norway, 2022). To identify the major sources, we utilized the database about CO_2 emissions from the land-based industry provided by the Norwegian Environment Agency (2021). We excluded the offshore petroleum industry from our research after consulting NGI's representative. Specifically, CO_2 from offshore sources stems mainly from the diesel/gas generators that produce power needed for drilling, oil and gas production and platform operations. Meanwhile, Norwegian industry is planning to electrify the platforms and thus CO_2 will be eliminated when diesel/gas generators are replaced by electricity from green sources such as wind power.

Based on the database, we selected the twenty largest CO_2 emitters whose CO_2 emissions are above 0.2 megatonnes (Mt). These emitters consist of one refinery, one petrochemical plant, two cement factories, four iron or steel plants, five aluminium plants, five silicon plants, and two facilities of other industries including production of fertilizers and natural gas processing. The CO_2 emissions per year for each of these sources vary between 0.225 Mt and 1.997 Mt, totaling to about 9.69 Mt of CO_2 emissions annually. The twenty selected sources account for approximately 74.7% of the total CO_2 emissions from all Norwegian sources of the land-based industry reported in 2021. In terms of the geographic locations, these sources mostly lie on the coast, and they are spread over different cities and regions in Norway. Specifically, 30% of the sources are situated in Western Norway while sources from Northern Norway and Southern Norway represent about one-fourth and one-fifth of the total respectively. Finally, there are only three plants in Southwestern Norway and two plants in central Norway. Details about the main activities, the annual CO_2 emissions, denoted as $Q_{n,p}$ [tonnes CO_2], and locations described by the exact coordinates of each source can be found in Appendix 2.

When it comes to CO_2 emissions distribution within the twenty selected sources, aluminium production is responsible for nearly 2.18 Mt of CO_2 annually, equivalent to 22% of the total emissions from these sources. Refinery contributes 1.997 Mt of CO_2 per year (21%), while silicon production contributes 1.46 Mt (15%), iron and steel production contributes 1.14 Mt (12%), and cement contributes 1.05 Mt (11%) per year. Additionally, other industrial domains, including natural gas processing, production of fertilizers and petrochemicals, result in a total of 1.86 Mt of CO_2 emissions annually, which corresponds to 20% of the total emissions. (Figure 4.3)

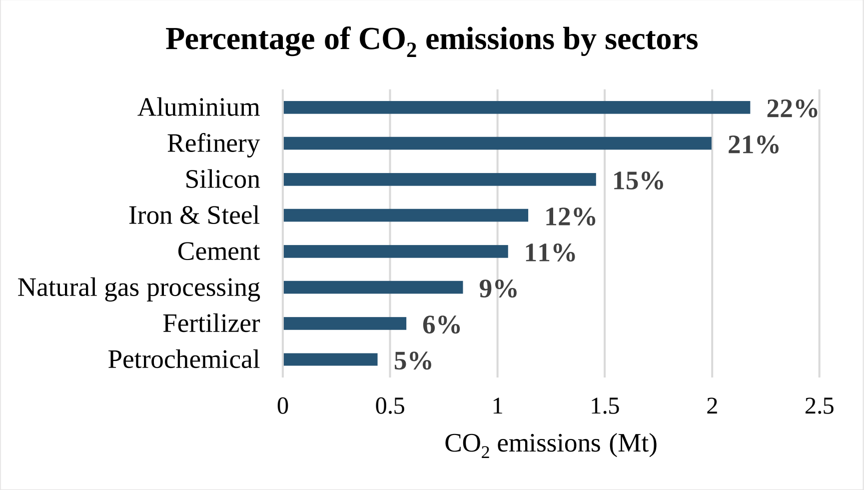
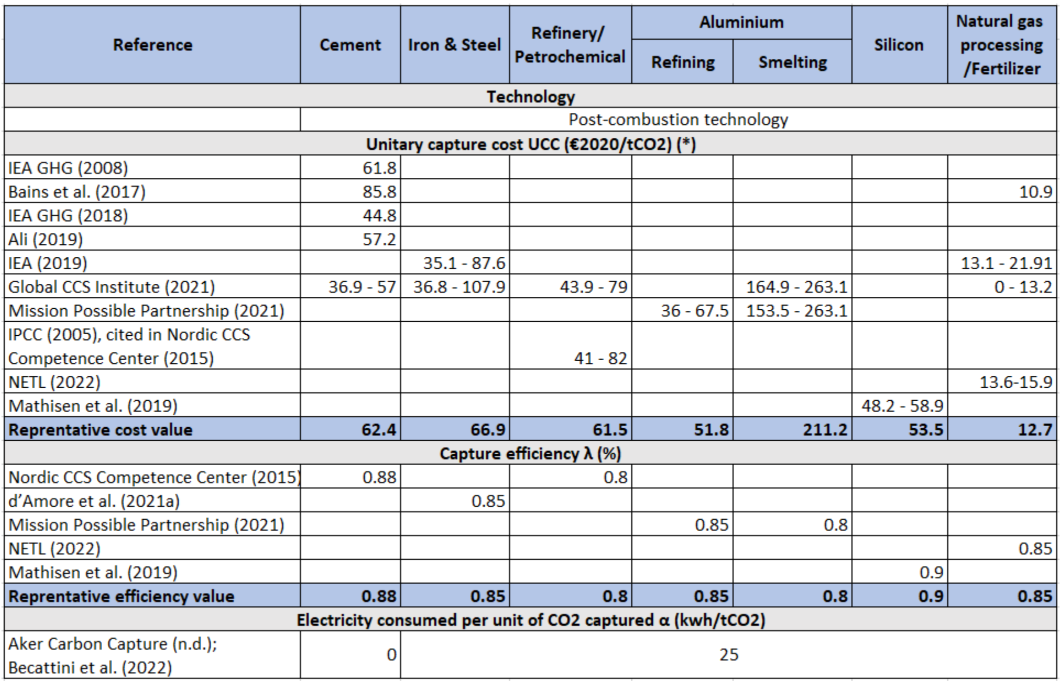


Figure 4.3. Distribution of CO_2 emissions within the selected sources by sectors

4.2.2. Capture

In our study, we select post-combustion technology as the method to capture CO_2 for all sectors. This technology was selected due to its relatively competitive cost, retrofit capability, commercial availability and its effectiveness in capturing CO_2 across various levels of CO_2 partial pressures. This choice was supported by literature review and particular references including Global CCS Institute (2021), Mission Possible Partnership (2021), Gardarsdottir et al. (2019), Bains et al. (2017) and d'Amore et al., (2021a).

With post-combustion technology being chosen, the key parameters used to describe the capture echelon include the unitary cost of capture, denoted as $UCC_{n,p}$ [€/tCO$_2$], which accounts for both capital and operation costs, the capture efficiency, represented by $\lambda_{n,p}$ [%], which measures the proportion of CO$_2$ emissions that are successfully captured and kept from being discharged into the atmosphere, and the electricity consumed per unit of CO$_2$ captured $\alpha^{c}_{n,p}$ [kWh/tCO$_2$]. These parameters are summarzed in Table 4.1. It is worth mentioning that all costs have been adjusted and standardized to a consistent economic reference point (specifically, the year 2020) using the chemical engineering plant cost index (CEPCI) provided in the Appendix 3 (Chemical Engineering, 2020).



Reference	**Cement**	**Iron & Steel**	**Refinery/ Petrochemical**	**Aluminium**		**Silicon**	**Natural gas processing /Fertilizer**
				Refining	**Smelting**		
Technology							
	Post-combustion technology						
Unitary capture cost UCC (€2020/tCO2) (*)							
IEA GHG (2008)	61.8						
Bains et al. (2017)	85.8						10.9
IEA GHG (2018)	44.8						
Ali (2019)	57.2						
IEA (2019)		35.1 - 87.6					13.1 - 21.91
Global CCS Institute (2021)	36.9 - 57	36.8 - 107.9	43.9 - 79		164.9 - 263.1		0 - 13.2
Mission Possible Partnership (2021)				36 - 67.5	153.5 - 263.1		
IPCC (2005), cited in Nordic CCS Competence Center (2015)			41 - 82				
NETL (2022)							13.6-15.9
Mathisen et al. (2019)						48.2 - 58.9	
Reprentative cost value	**62.4**	**66.9**	**61.5**	**51.8**	**211.2**	**53.5**	**12.7**
Capture efficiency λ (%)							
Nordic CCS Competence Center (2015)	0.88		0.8				
d'Amore et al. (2021a)		0.85					
Mission Possible Partnership (2021)				0.85	0.8		
NETL (2022)							0.85
Mathisen et al. (2019)						0.9	
Reprentative efficiency value	**0.88**	**0.85**	**0.8**	**0.85**	**0.8**	**0.9**	**0.85**
Electricity consumed per unit of CO2 captured α (kwh/tCO2)							
Aker Carbon Capture (n.d.); Becattini et al. (2022)	0	25					

(*) All costs have been standardized to €$_{2020}$ using the chemical engineering plant cost index and exchange rate from (Exchange Rates, n.d.)

Table 4.1. Parameters for capture process

As for the electricity utilized for CO$_2$ capture process, it is important to note that this parameter for cement plants is set to be zero. The world's first CO$_2$ capture facility at a cement plant is being installed and will be in operation by 2024 at Heidelberg materials Brevik (Brevik CCS, n.d.), one of the two CO$_2$ sources from cement production considered in this thesis. This facility uses waste heat recovered from the cement plant to capture CO$_2$ (Aker Carbon Capture, n.d.), thus there are no additional emissions caused by the electricity requirements for running the capture system. For other industrial sectors, while the necessary heat for CO$_2$ capture can potentially be provided internally by the plant or from renewable sources, we consider an electrical energy demand of 25 kWh/tCO$_2$ for the purpose of model generalization. This number is taken from Becattini et al. (2022).

4.2.2.1. Cement

The primary source of CO_2 emissions in cement production is the rotary kiln, where CO_2 is released from both the combustion of fuel and the process of limestone calcination (i.e., decomposition of carbonate minerals). This combination of process and combustion emissions occurs within a single unit in cement production (Bains et al., 2017). The cement industry presents a favourable prospect for CCS due to several factors. Cement plants are relatively significant emitters of CO_2, and the concentration of CO_2 in their flue gas is relatively high. Additionally, around 60% of the CO_2 emissions stem from the calcination process, which cannot be mitigated by alternative energy sources (IEA GHG, 2008; Barker et al., 2009)

For cement plants, pre-combustion capture is not a viable option since it can only capture the CO_2 emissions generated from the fuel used, rather than the larger quantity of CO_2 resulting from carbonate mineral decomposition (IEA GHG, 2008; Nordic CCS Competence Center, 2015). Evaluation of post-combustion and oxy-fuel capture, the two most potential technologies for carbon capture in a cement factory, reveals that while the latter is cheaper, the former is more technologically ready and easily retrofitted to existing facilities (IEA GHG, 2008; IEA GHG, 2013; Gardarsdottir et al., 2019).

Heidelberg materials Brevik has invested and engaged in different projects for research and development of carbon capture technologies (HeidelbergCement, n.d.). At the end of 2019, Heidelberg materials Brevik, together with other three European cement manufacturers, established the joint research project called Catch4Climate which aims to assess the feasibility of implementing oxy-fuel carbon capture in the process of cement production through a pilot project in Southern Germany (HeidelbergCement, 2019). Although oxy-fuel technology holds promising prospects for practical development and large-scale implementation in the coming years, post-combustion technology is still preferred at present. Indeed, for the first full-scale project in Norway – Longship, Heidelberg materials Brevik will capture CO_2 based on the amine-based post-combustion technology. For that reason, we also consider post-combustion technology for cement plants in this study.

Coming to the unitary capture cost, IEA GHG (2008) estimated the cost corresponding to post-combustion technology to be \$59.6 per tonne of CO_2 captured from cement plants, which is equivalent to 61.8 €$_{2020}$/tCO_2. This is calculated based on the cost difference between cement factories with and without CO_2 capture in terms of capital costs, cement production costs, and operating costs including fuel and power cost, fixed operating costs, capital charges and other variable costs. More recently, IEA GHG (2018) found that the CO_2 captured cost when using advanced amine-based post-combustion technology is 45 \$$_{2016}$/t$CO_2$, equivalent to 44.8 €$_{2020}$/t$CO_2$. This cost includes both capital and operation and maintenance (O&M) costs. Capital cost elements consist of process equipment, supporting facilities, direct and indirect labour, engineering services, procurement and construction costs, process contingency, project contingency, pre-production costs, inventory capital, financing costs and other owner's costs, interest during construction and cost escalations during construction. Meanwhile, O&M cost items include operating, supervision, maintenance, administrative and support, maintenance materials, property taxes and insurance, fuel, other consumables such as catalyst and chemicals, waste disposal and by-product sales.

The cost of carbon capture using post-combustion technology is also collected from Bains et al. (2017), Ali (2019) and Global CCS Institute (2021) to verify consistency. Finally, a representative value of 62.4 €$_{2020}$/tCO_2 is applied in this thesis. In terms of capture efficiency, it is reported to be 88% in a case study developed by Nordic CCS Competence Center (2015) for post-combustion carbon capture from the cement production process of Heidelberg materials Brevik. This number will therefore be used as the input for the capture rate of the cement sector in our model.

4.2.2.2. Iron and Steel

Unlike cement plants, steel mills exhibit varying levels of complexity in the capture process since CO_2 emissions arise from multiple process units. In particular, the primary sources of carbon emissions in an integrated iron and steel mill are power plant, blast furnace stoves, coke ovens, sinter plant and lime kiln. Among these, the power plant contributes 37% of the total CO_2 emissions, followed by stoves (19%), coke ovens (17%) and the sinter plant (17%), collectively generating a substantial portion of the overall emissions. (Nordic CCS Competence Center, 2015; d'Amore et al., 2021a).

According to Nordic CCS Competence Center (2015), all major technologies for carbon capture can potentially be used to capture CO_2 from iron and steel mills. While oxy-fuel and pre-combustion processes might be more efficient (IPCC, 2007; Manzolini et al., 2020), we here consider post-combustion capture from emission points as it offers higher technology readiness level, an easier retrofit and more available cost data (d’Amore et al., 2021a).

While we acknowledge that the optimal technology for capturing CO_2 and CO_2 capture cost will be contingent on the emission point since CO_2 is generated from various process units, we assume a single capture technology and a uniform cost value for iron and steel sector. This assumption is made to simplify the model and overcome data shortage. Accordingly, we collect unitary cost of post-combustion capture from Global CCS Institute (2021), which considers both the capital and operating expenses of the plant with an assumption of an 8% cost of capital over a span of 30 years. Cost data is also extracted from IEA (2019) for comparison, and a representative value of 66.9 $€_{2020}/tCO_2$ is used in this study. Furthermore, a capture rate of 85% is collected from d’Amore et al. (2021a) and applied here.

4.2.2.3. Refinery and Petrochemical

Similar to iron and steel industry, petroleum refineries are characterized by numerous CO_2-producing units that necessitate various separation processes (Leeson et al., 2019). In addition, each refinery has its own unique configuration designed to produce a specific range of products, depending on the type of petroleum feedstock used. As a result, a carbon capture design developed for one refinery is unlikely to fit another refinery (Bains et al., 2017). This characteristic, together with the dispersed nature of emission points, makes the implementation of CCS for refineries challenging.

In general, the primary sources of CO_2 emissions in a refinery stem from process heaters, fluid catalytic cracker, utilities, and hydrogen production, although not all refineries have these units. Process heaters contribute between 30-60% of the total emissions, while utilities, including on-site steam and electricity generation, can make up 20-50% of the overall CO_2 emissions. A fluid catalytic cracker and hydrogen production unit can be responsible for 20-50% and 5-20% of a refinery’s CO_2 emissions respectively (Bains et al., 2017). Besides, a refinery can contain CO_2 sources not suitable for the capture process owing to their relatively small size. As a result, the overall capture rate in a refinery may be less than 85%-90% which is achievable on an individual stream (Nordic CCS Competence Center, 2015).

Therefore, with post-combustion technology being used, we assume an overall capture efficiency of 80%.

Research and reports conducted by IPCC (2005), Melien (2005), Collodi (2010), Meerman et al. (2012), Berghout et al. (2013) and Global CCS Institute (2021) have examined carbon capture in refineries, with the majority focusing on post-combustion technology. It could be concluded that there is a significant variation in the cost estimations, which is primarily influenced by the diverse characteristics and complexities of different refineries. In this thesis, we base on IPCC (2005) and Global CCS Institute (2021) to derive a representative value of 61.5 $€_{2020}/tCO_2$ for the unitary capture cost in a refinery.

Coming to petrochemical plants, they have some similar sources of CO_2 emissions as petroleum refineries due to their common operations within the oil and gas industry (Global CCS Institute, 2021). The processes contributing to the release of CO_2 into the atmosphere involved in both types of facilities include feedstock processing, energy generation, flaring/venting and chemical reactions. Considering this and the lack of documented cost data for petrochemical plants, we assume that the unitary capture cost and capture efficiency of these plants are the same as refineries.

4.2.2.4. Aluminium

According to IEA (2022), alumina refining and aluminium smelting contribute to more than 90% of the direct CO_2 emissions associated with aluminium production. Based on the greenhouse gas emissions data for the aluminium sector collected from International Aluminium (2021), we here assume that alumina refining and aluminium smelting are responsible for 15% and 79% of the CO_2 emissions from aluminium production respectively. In this study, we also only consider capturing CO_2 emissions from these two processes.

A challenge for the application of CCS technology to the aluminium production process is the low concentrations of CO_2 in its flue gas (Mission Possible Partnership, 2021). Indeed, the CO_2 concentration in the flue gas from aluminium smelters is just around 1%, while existing capture technologies have mainly focused on capturing emissions from energy production and other industrial sectors that have higher CO_2 concentrations, usually exceeding 4% (Hydro, 2022a). This translates to a very high cost of capturing CO_2 from aluminium smelters.

Specifically, absorption-based post-combustion technology could be used to capture CO_2 during the smelting process at a cost of 175-300 $\$_{2020}$/tCO2 (capital and operation costs included) according to Mission Possible Partnership (2021). This cost range is compared with data from Global CCS Institute (2021) to determine a representative capture cost of 211.2 $€_{2020}/tCO_2$ for aluminium smelters.

Recently, Norsk Hydro, one of the largest aluminium companies worldwide, have announced that it has conducted assessments of over 50 CCS technologies to capture CO_2 from existing smelters and established a roadmap for piloting the most promising options on an industrial scale. The target is to have a large-scale pilot program in operation by 2030, contributing to accelerate the decarbonization process of the aluminium industry and ensure the adaptability of the current aluminium smelters for the future (Hydro, 2022b). This ambition from Hydro is expected to help reduce the cost of capturing CO_2 from aluminium smelters significantly and thus make it economically feasible. However, data about this has yet to be available for us to use. The model input can therefore be updated along with the progress of Hydro's project.

When it comes to carbon capture from alumina refineries, it offers a better value case due to the higher concentration of CO_2 in the flue gas, although it can differ significantly based on the specific refinery. As estimated by Mission Possible Partnership (2021), the cost of carbon capture for alumina refineries with absorption-based technology could range from 41 to 77 $\$_{2020}$/tCO2, equivalent to from 36 to 67.5 $€_{2020}/tCO_{2,}$. A representative value of 51.8 $€_{2020}/tCO_2$ is then derived based on that.

In terms of capture efficiency, the aluminium industry may encounter challenges mainly because of flue gas composition. Apart from the CO_2 concentration, certain flue gas streams from smelters can contain excessive amounts of sulphur dioxide (SO_2) or oxygen, which hinders good capture rates of more than 85% (Mission Possible Partnership, 2021). For this reason, we assume capture efficiencies of 85% for alumina refineries and 80% for aluminium smelters as our model inputs.

4.2.2.5. Silicon

With an annual silicon production of 360000 metric tonnes reported in 2022, the Norwegian silicon industry has established itself as the fourth largest globally (USGS, 2022). The overall CO_2 emissions from silicon production in Norway are among the lowest in the world, primarily due to high energy efficiency and Norway's predominant use of hydro power for electricity generation (Statistics Norway, 2023). However, the industry's contribution to CO_2 emissions in Norway remains substantial as a result of the carbon-based raw materials consumed during the production process (Mathisen et al., 2019).

At the 10th Trondheim Conference on CCS in 2019, the paper "CO_2 capture opportunities in the Norwegian silicon industry", published by SINTEF, was presented. Two silicon production plants have been examined for the integration with a capture plant using MEA-based post-combustion technology. The first silicon plant is a small one that produces around 55 kilotonnes (kt) of CO_2 per year and has a low CO_2 concentration in the flue gas. Consequently, the capture cost was considerably high, around 120 $€_{2015}/tCO_2$. Meanwhile, the second plant, a larger facility with an annual CO_2 production of about 250 kt and a higher CO_2 concentration in the flue gas, had the capture cost ranging between 45 and 55 $€_{2015}/tCO_2$ captured (Mathisen et al., 2019). These costs were estimated by determining the investment, operation and maintenance costs in each case.

Given that all the sources examined in our study emit more than 200 kt CO_2 annually, the cost data for the second plant is more relevant. Furthermore, the paper also shows that it is potential to achieve a capture rate of 90% successfully for both plants (Mathisen et al., 2019). As a result, a representative capture cost of 53.5 $€_{2020}/tCO_2$ and capture efficiency of 90% are selected as the input for the silicon industry in our model.

4.2.2.6. Fertilizer and natural gas processing

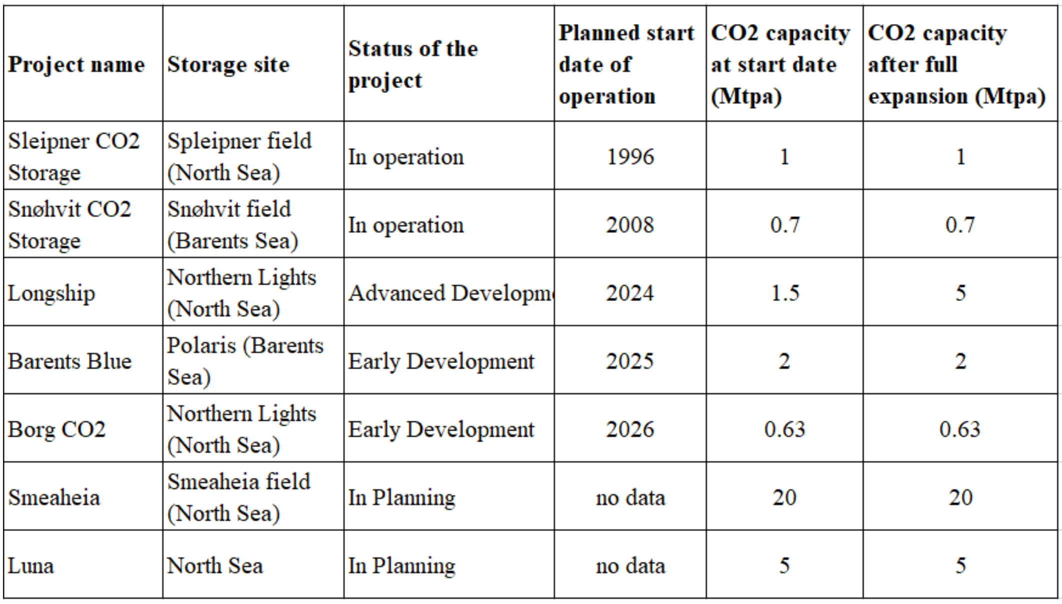
Fertilizer production and natural gas processing are two industries that produce pure or highly concentrated CO_2 streams (more than 95% by volume), which make capturing CO_2 from them relatively low-cost compared to other industries (IEA, 2019). According to IEA (2019), the capture cost from these high purity industrial sources can range from 15-25 $\$_{2019}/tCO_2$. Also, it can be seen from Global CCS Institute (2021) that the costs of capturing CO_2 from natural gas processing and fertilizer production, including both capital and operating costs but excluding downstream CO_2 compression, both vary between 0-15 $\$_{2020}/tCO_2$. Furthermore, data from Bains et al. (2017) and the most recent report of capture cost from NETL (2022) are acquired for comparison. Finally, a representative cost value of 12.7 $€_{2020}/tCO_2$ is obtained. Regarding capture efficiency, the value of 85% from NETL

(2022) is chosen for our study.

4.2.3. Storage

4.2.3.1. CO_2 storage projects in Norway

The Norwegian continental shelf holds immense possibilities for storing CO_2 on a large scale, and it is crucial to guarantee the integrity of the stored CO_2 and prevent any leakage. Thus, storing CO_2 beneath the ocean floor is the safest choice in Norway. There exist substantial geological formations deep under the seabed that offers ideal temperature and pressure conditions effectively inhibiting the upward movement of CO_2 through rock layers towards the seabed (Norskpetroleum, 2023a). Table 4.2 gives an overview of existing and planned projects involving CO_2 storage in Norway.



Project name	**Storage site**	**Status of the project**	**Planned start date of operation**	**CO2 capacity at start date (Mtpa)**	**CO2 capacity after full expansion (Mtpa)**
Sleipner CO2 Storage	Spleipner field (North Sea)	In operation	1996	1	1
Snøhvit CO2 Storage	Snøhvit field (Barents Sea)	In operation	2008	0.7	0.7
Longship	Northern Lights (North Sea)	Advanced Developm	2024	1.5	5
Barents Blue	Polaris (Barents Sea)	Early Development	2025	2	2
Borg CO2	Northern Lights (North Sea)	Early Development	2026	0.63	0.63
Smeaheia	Smeaheia field (North Sea)	In Planning	no data	20	20
Luna	North Sea	In Planning	no data	5	5

Table 4.2. Overview of existing and planned CO_2 storage projects in Norway

(IOGP, 2023; ZEP, n.d.; Wintershall Dea, 2022)

Norway has extensive experience in the field of CO_2 storage in a reservoir. The Sleipner project, the first offshore CCS implementation worldwide, has been in operation since 1996. By the end of 2020, 19 Mt CO_2 from the production of natural gas at Sleipner area has been captured and injected into the Utsira saline formation which is 800 meters under the seabed (Equinor, n.d.-b). Similar to Spleipner, Snøhvit is an offshore gas field. Situated in the Northern Norway, it provides gas to the Melkøya LNG (liquified natural gas) production plant. As the natural gas extracted from this field contains 5% to 6% CO_2, it has been separated and piped back to Tubaen formation for permanent storage at 2600 meters depth in the Barents

Sea since 2008 (Equinor, 2008; IOGP, 2023). Currently, the CO_2 storage projects at Spleipner and Snøhvit stand as the sole operational projects of their kind in Europe, and they are also unique within the offshore industry (Norskpetroleum, 2023a).

When it comes to the Longship project, as introduced earlier in this thesis, it is a full-scale CCS project aimed at the effective capture, transportation and secure storage of CO_2 from industrial domains. The process involves capturing CO_2 at Hafslund Oslo Celsio's waste-to-energy facility and Heidelberg materials Brevik's cement plant. Afterward, the liquefied CO_2 will be transported by ship to an intermediate storage site at Øygarden which is located in the Northwest of Bergen. It is then pumped through a pipeline to the Northern Lights storage site below the Norwegian North Sea. Initially, the Northern Lights storage site has a capacity of storing 1.5 million tonnes of CO_2 annually. However, the project has the vision to increase the storage capacity to 5 million tonnes annually through a subsequent development phase and by expanding capture sites in Norway and other countries. (Norwegian Ministry of Petroleum and Energy, n.d.; CCS Norway, n.d.-b)

Next, the Barents Blue project aims to become Europe's first large-scale plant for production of blue ammonia and blue hydrogen (Horisont Energi, n.d.). The CO_2 generated during the production process will be captured and stored permanently in the Polaris aquifer in the Barents Sea with the rate of CO_2 injection per year estimated to be 2 Mt (IOGP, 2023). In terms of Borg CO_2, the project's goal is to create a CCS cluster within the Borg port area, capable of capturing around 0.63 Mt CO_2 annually (IOGP, 2023). This will involve capturing CO_2 from five different industrial facilities and transporting it through onshore pipelines to the terminal located at the Port of Borg. At the terminal, the CO_2 will be liquefied and transported to the intermediate storage terminal at Øygarden before being injected into the Aurora aquifer of the Northern Lights project for permanent storage (Borg CO2, n.d.).

Finally, Smeaheia and LUNA projects are still in the planning stage. Smeaheia, a notable fault block situated in the Norwegian North Sea, has been identified as a potential site for CO_2 storage. Equinor, the operator, has already submitted proposals for the field's development, which includes plans for a CO_2 storage capacity of 20 Mt annually (Equinor, 2022b). Meanwhile, Wintershall Dea has recently been awarded the Luna license for CO_2 storage in the Norwegian North

Sea. Luna is located 120 kilometers west of Bergen and is projected to hold a CO_2 storage capacity of up to 5 Mt per year (Wintershall Dea, 2022).

4.2.3.2. Selected storage sites

As mentioned before, Spleipner and Snøhvit are currently in operation. From the interview with the senior specialist in NGI, there are no plans to expand the capacity of these two storage sites. Coming to the Polaris aquifer in the Barents Sea, it is used specifically for the Barents Blue project. Thus, Northern Lights, Smeaheia and Luna are three potential storage sites that we will consider for our study. Table 4.3 summarizes information about location, geological storage type, capacity and unitary storage cost of these three storage sites.

Storage site	**Northern Lights**	**Smeaheia**	**Luna**
Intermediate onshore storage location	The Energy Park – Øygarden, Northwest of Bergen (Northern Lights, n.d.-b)	Not applicable	Not applicable
Offshore storage location	70 km west of Bergen (Riviera, 2022). Connect with onshore terminal by a 100-km-long pipeline (Northern Lights, n.d.-b)	50 km west from Mongstad (CO2datashare, n.d.)	120 km west of Bergen (Wintershall Dea, 2022)
Geological storage type	Saline aquifer at 2600 meters depth (Northern Lights, n.d.-b)	Saline aquifer at 890-1300 meters depth (CO2datashare, n.d.)	Saline aquifer (Wintershall Dea, 2022)
Capacity (Mtpa)	5 (Northern Lights, n.d.-b)	20 (Equinor, 2022b)	5 (Wintershall Dea, 2022)
Unitary storage cost (€/tCO2)	20 (d'Amore et al., 2021a; interviews)		

Table 4.3. Characteristics of three selected storage sites

From Table 4.3, all three storage sites are characterized as deep saline aquifer which has been concluded in the literature review as one of the best sites for large-scale disposal of CO_2. These offshore storage sites are quite close to each other; however, they have different capacities and specifications. The intermediate onshore terminal where CO_2 is transported to before being pumped through a 100-kilometer-long pipeline to the Northern Lights storage site is the Energy Park in Øygarden while this information is unavailable for Smeaheia and Luna. Therefore, for our model inputs, we assume that the onshore terminals of Smeaheia and Luna are the same as Northern Lights.

As for the unitary storage cost, 18 €/tCO2 is the number taken from d'Amore et al., (2021a). However, from our interviews with a special adviser in the Research Council of Norway and a senior specialist at NGI, CO_2 storage cost might currently be in the range of 10 to 40 €/tCO_2, and the learning curve can help to reduce this cost in the future. In our thesis, we thus set the unitary storage cost to be 20 €/tCO_2.

4.2.4. Transport

In Norway, while trucks are considered in CCS projects, CO_2 are mostly transported via pipelines or ships. Currently, Norway has two CCS projects in operation, Sleipner and Snøhvit projects. For Sleipner project, there is no need to use transportation mode to transmit CO_2 as CO_2 is captured at the Sleipner field and injected back into the underground, whereas pipelines are used to transfer CO_2 from capture sites to storage sites in Snøhvit project. In 2020, the Norwegian government invested in developing the first large-scale CCS project in Norway, Longship project. In this project, the captured CO_2 is transported by ships to an onshore receiving terminal and then transported by pipeline from there to the offshore storage site. (Norskpetroleum, 2023b). For truck transportation in Norway, although not being utilized in CCS yet, CO_2 transported via trucks is examined for short distance in some projects. For example, Hafslund Oslo Celsio, a participant of the Longship project, is planning to use truck to transfer CO_2 from Klemetrud to Oslo Harbor.

Following literature and practical experience, pipelines and ships are deemed to be the most popular and efficient transportation modes in CCS, especially for large-scale projects. Besides, trucks also have the potential to transport CO_2 for short distances. Another option for onshore CO_2 transportation is railway; however, owing to the lack of data on available rail routes, it is chosen to neglect railway transport from this study. As a result, this thesis is decided to examine three types of transport technologies: pipelines, ships, and trucks.

In the mathematical model, those transport technologies are expressed through set B = *{pipe, ship, truck}*, respectively referring to pipeline transport, ship transport and truck transport. The set of sizes of transport technologies is indicated with Z. Z includes two subsets: $Z^{pipe} = \{z_{1-6}\}$ and $Z^{ship} = \{z_{1-5}\}$, respectively corresponding to sizes of the pipeline transport and sizes of the ship transport.

To assess the cost performance and environmental impacts of the transport process, data on distance between two nodes, unitary cost of transport, loss of CO_2 during transporting and emissions of each transport technology are required for our model. Among these, the loss of CO_2 during transporting (θ_b) and emissions of each transport technology, comprising direct emissions (μ_1^b) and indirect emissions (μ_2^b), are derived from Becattini et al. (2022) and are illustrated in Table 4.4. The detailed characteristics of other data are described for each transport technology in the following parts.

Technology	**Loss of CO_2 during transporting (θ) (tCO_2/km)**	**Direct emissions (μ_1) (tCO_2/tCO_2/km)**	**Indirect emissions (μ_2) (tCO_2-eq/tCO_2/km)**
Pipeline	$2 \text{ x } 10^{-6}$	$1.55 \text{ x } 10^{-6}$	$3.15 \text{ x } 10^{-6}$
Ship	10^{-6}	$9.6 \text{ x } 10^{-7}$	$8.4 \text{ x } 10^{-6}$
Truck	10^{-6}	$6.83 \text{ x } 10^{-5}$	$2 \text{ x } 10^{-6}$

Table 4.4. Parameters describing loss of CO_2 during transportation and emissions of transport technologies

4.2.4.1. Pipeline

In this model, pipelines can be installed between CO_2 sources, ports, and storage sites. As suggested from existing literature, the condition for CO_2 transported via pipelines is set to be in dense phase at 100 bar and ambient temperature. In terms of the pipeline design, as there are no detailed maps of current pipeline routes in Norway and to reduce the complexity of the model, the length of pipeline connections is considered the shortest distances between two nodes. Particularly, the distances for pipeline are based on straight paths between two nodes and calculated using Google maps. However, Norwegian geography often requires pipeline to go through difficult terrain comprising valleys, mountains, and solid basement rock, causing higher construction cost of pipeline than general condition (Kjärstad et al., 2016). Hence, a terrain factor, β, of 10% is added to the pipeline distances to account for the challenging characteristics of the Norwegian landscape.

Moreover, a discretization of transport flowrate, F_z, in six sizes z = {1, 2, …, 6} (Table 4.5) is employed. These sizes define corresponding ranges of admissible flowrates, [F_z^{min} - F_z^{max}] [tCO_2/year]. The discretization allows the pipeline transport cost function to remain linear as the flowrate increases, although the effect of economies of scale may cause non-linear function of the pipeline transport cost over the flowrate of CO_2.

When it comes to the cost data, total transport cost via pipeline is related to the unitary cost of pipeline transport (UTC^{pipe}[€/tCO_2/km]), amount of CO_2 transported and total travel distance. To obtain the unitary transport cost of pipeline, some previous literature has been considered. For example, Global CCS Institute (2021) presents a report analyzing unitary transport cost of pipeline in which they consider both annual capital cost and operating cost. The unit cost of pipeline transport is also provided in d'Amore et al. (2021a). As a result, the unitary cost for pipeline transport was retrieved based on the average of corresponding data collected from these two sources. Table 4.5 shows different sizes for the pipeline option and the unitary cost for each size.

Size z	**Range**		**Unitary cost of transport for pipeline (UTC^{pipe}[€/tCO_2/km])**		
	F_z^{min} [tCO_2/year]	**F_z^{max} [tCO_2/year]**	**d'Amore et al. (2021a)**	**Global CCS Institute (2021)***	**Representative value**
z_1	40 000	250 000		0.1836	0.1836
z_2	250 000	500 000	0.0855	0.0921	0.0888
z_3	500 000	1 000 000	0.0537	0.0710	0.0624
z_4	1 000 000	2 000 000	0.0337	0.0588	0.0462
z_5	2 000 000	5 000 000	0.0183	0.0427	0.0305
z_6	5 000 000	10 000 000	0.0183		0.0183

**A USD/EUR average exchange rate of 0,877 (2020) was applied*

Table 4.5. Unitary cost of pipeline transport

4.2.4.2. Ship

In addition to pipeline, ship is another offshore transport option. In this study, ship transportation is modelled to be available between two ports or between ports and storage sites. The distance for ship transport is derived from the information available on the websites ports.com. Based on the existing literature, it is determined that the CO_2 transported by ships will be in the liquid phase under specific conditions of 7 bar pressure and a temperature of -50°C. Additionally, given the immaturity of offshore unloading from ship, the focus of this thesis is primarily on the shore-to-shore scenario.

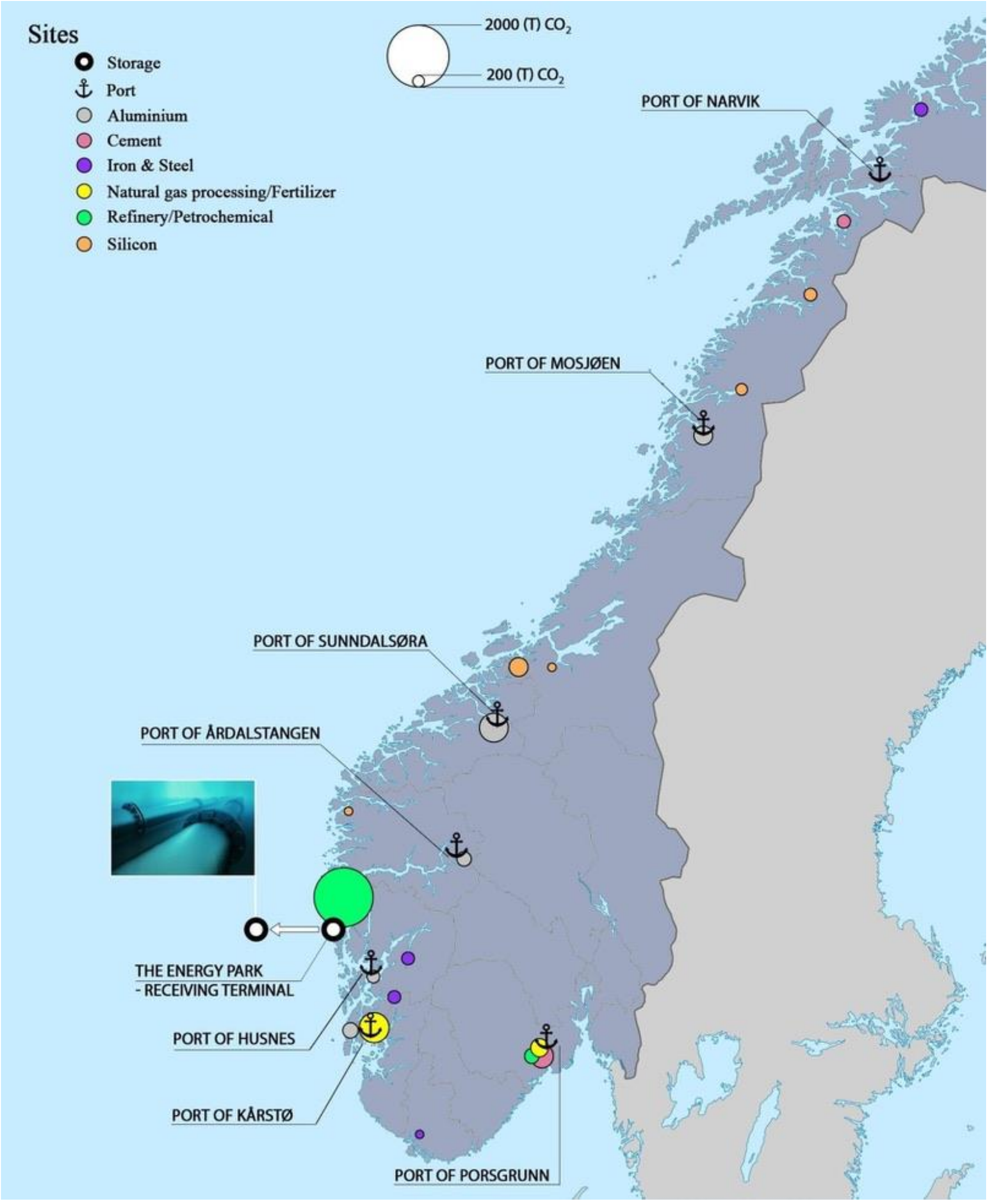


Figure 4.4. Illustration of the considered ports

Regarding identifying potential port for CO_2 transmission, seven ports have been included in the model, namely Port of Narvik, Port of Mosjøen, Port of Porsgrunn, Port of Sunndalsøra, Port of Årdalstangen, Port of Husnes and Port of Kårstø

(Figure 4.4). These ports were chosen based on careful consideration of various factors, including their distribution throughout Norway, proximity to the CO_2 sources being studied, storge capacity, existing infrastructure, and accessibility. The Port of Narvik and Port of Mosjøen are situated in Northern Norway. The Port of Porsgrunn covers the sources in Southern Norway, while the Port of Sunndalsøra is situated in Central Norway. Additionally, the Port of Årdalstangen, Port of Husnes and Port of Kårstø have been selected for the region of Western and Southwestern Norway. All of the port candidates are located in close proximity to several plants in the region (the coordinates of the ports are shown in Appendix 4). They have well-established infrastructure for the storage and handling of various cargoes, including CO_2. Besides, they are easily accessible with good connections to road networks, facilitating efficient transportation of CO_2 from the industrial facilities in the region.

In terms of the ship transport cost, there have been several works analyzing costs of ship transport, such as Aspelund et al. (2006), Bjerketvedt et al. (2020), Decarre et al. (2010), Kjärstad et al. (2016), Orchard et al. (2021), Ozaki et al. (2013), ZEP (2011), etc. Among these, the work of Kjärstad et al. (2016) investigates CO_2 ship transport cost in Nordics countries over a wide range of transported flowrates. To produce cost estimation for ship transport, they took into account the costs of conditioning, loading, unloading, port fee and intermediate storage (with a buffer storage capacity equal to the capacity of the ship). More recently, Orchard et al. (2021) analyzed the economic performance of the ship-based CO_2 transport and displayed a detail result of the ship transport cost.

In this model, the ship transport cost is calculated by multiplying the flowrate of CO_2 transported by a linear equation with respect to the travelled distance. This equation is characterized by coefficients for the slope $UTC_z^{ship,s}$[€/tCO_2/km] and the intercept $UTC_z^{ship,i}$[€/tCO_2], which vary across five different sizes of the ship transport. The slope and intercept coefficients are calculated from the findings of Kjärstad et al. (2016) and Orchard et al. (2021). Accordingly, the ship transport cost here comprises the costs of conditioning, loading, unloading, intermediate storage and port fee. In addition, five sizes of ship, which are equivalent to different ranges of admissible ship flowrates, [F_z^{min} - F_z^{max}] [tCO_2/year], are applied to maintain the linearity in the function of ship transport cost. Table 4.6 demonstrates five sizes of ship transport and corresponding slope and intercept coefficients.

Size z	**Range**		**Slope coefficient of unitary cost of ship transport ($UTC_z^{ship,s}$ [€/tCO₂/km])**	**Intercept coefficient of unitary cost of ship transport ($UTC_z^{ship,i}$ [€/tCO₂])**
	F_z^{min} [tCO₂/year]	**F_z^{max} [tCO₂/year]**		
z_1	40 000	500 000	0.0096	27.28
z_2	500 000	1 000 000	0.0085	21.60
z_3	1 000 000	2 000 000	0.0068	17.29
z_4	2 000 000	5 000 000	0.0030	11.89
z_5	5 000 000	10 000 000	0.0015	11.59

Table 4.6. Slope and intercept coefficients of unitary cost of ship transport

4.2.4.3. Truck

Given the potential of truck-based transport for short distances and the lack of data for transporting CO_2 by truck over long distances, our model only includes the truck option for distances of less than 100 kilometers. All the truck distances in our study were taken from Google map. As a longer distance implies a lower unitary truck transport cost, we further defined two different distance ranges for truck $d \in U$ $(U = \{d_{1\text{-}2}\})$, as shown in Table 4.7, to keep the truck transport cost function linear when the travelled distance increases. Accordingly, a parameter $k_{n,n',d}$ indicating whether the truck distance is within the distance range *d* is introduced to the model. $k_{n,n',d}$ can only take 0 or 1 values, in which 1 means the distance via trucks from node n to n' is within d and 0 otherwise. Similar to ship transport, CO_2 is transmitted via trucks in liquid form at 7 bar and 20°C using tankers.

Concerning the cost data for truck transport, in this thesis, it is modeled based on the unitary cost of truck transport (UTC^{truck}[€/tCO₂/km]), transported flowrate of CO_2 and travelled distance. The unitary cost of truck transport was first considered from limited existing literature. Stolaroff et al. (2021) displayed some numbers for CO_2 truck transport. However, they considered a total travelled distance of around 200km only. Later, truck transport cost data for the same and smaller distances were collected from the interview with Halsfund Oslo Celsio. This data considers driving cost, loading and unloading cost as well as buffer cost for car queue. Finally, a representative cost values for different ranges used in this model was decided, as illustrated in Table 4.7.

Distance d	**Range**		**Unitary cost of transport for truck (UTC^{truck}[€/tCO2/km])**		
	D_d^{min} [km]	**D_d^{max} [km]**	**Stolaroff et al., (2021)***	**Halsfund Oslo Celsio, (personal communication) (2023)**	**Representative value**
d_1	0	75		0.240	0.24000
d_2	75	100	0,0973	0.086	0.09165

** A USD/EUR average exchange rate of 0,877 (2020) was applied*

Table 4.7. Unitary cost of truck transport

4.2.5. Conditioning

CO_2 is captured and transported at different levels of temperature and pressure, for example: after capturing, the CO_2 is generally at ambient pressure and temperature (assuming at 1 bar and 15°C) (Engel & Kather, 2017), or the state of CO_2 transported via pipeline needs to be at 100 bar and ambient temperature. Therefore, to transport CO_2, conditioning process, including cooling, compressing, and liquefying, is required in the CCS system to bring CO_2 to appropriate standard of corresponding transportation modes. In this model, we consider that at each node, CO_2 is required to be conditioned when moving from capture plants to transportation modes (i.e. pipeline or truck) or switching between two different transport technologies. Additionally, we assume that equipment required for CO_2 conditioning is available at each node, including capture sites, storage sites and ports, to provide any required work to achieve suitable standards for CO_2 transport.

In order to investigate the emissions of the system, the electrical energy required for conditioning, *G*, is considered. The energy consumption exhibits a positive value when there is an increase in pressure and a decrease in temperature, while it remains at zero when cooling and compression are unnecessary. In the model, *G* is computed based on the amount of CO_2 transported and energy consumed to bring one tonne CO_2 from one condition to other condition, including from capture condition to pipeline condition (ψ_1 [kWh/tCO2]), from capture condition to truck condition (ψ_2 [kWh/tCO2]), from pipeline condition to ship or truck condition (τ_1[kWh/tCO2]), and from ship or truck condition to pipeline condition (τ_2[kWh/tCO2]). ψ_1, ψ_2, and τ_1 are taken from existing papers in which they conducted analysis of energy consumption when adjusting relevant conditions of

CO_2. However, due to the lack of data, τ_2 is assumed to be around and lower than $\psi_1$because: (1) when moving CO_2 from ship/truck to pipeline, there is no energy needed for increasing temperature; (2) compressing CO_2 from 7 bar to 100 bar requires less energy than from ambient pressure to 100 bar. Table 4.8 displays energy consumption to adjust conditions of CO_2.

Condition	**Parameter**	**Energy consumption (kWh/tCO_2)**	**Reference**
From capture to pipeline	ψ_1	85	Bilsbak (2009)
From capture to ship/truck	ψ_2	105	Gong et al. (2022)
From pipeline to ship/truck	τ_1	23	Engel & Kather (2017)
From ship/truck to pipeline	τ_2	80	

Table 4.8. Energy consumption for conditioning

4.3. Mathematical formulation

This section will explain the mathematical formulation of the multi-stage, multi-echelon, static MILP model for designing an optimal CO_2 supply chain network. First, the list of input data will be displayed and then, the objectives of the model will be explained. Later, the decision variables or the outputs of the model will be defined and finally, the constraints will be expressed as inequalities or equations.

4.3.1. Summary of input data

All input data used for the model is displayed in Table 4.9 below.

Name	**Input data**	**Condition**	**Description**
Unitary capture cost (€/tCO_2)	$UCC_{n,p}$	$n \in N^c$ $p \in P$	Cost of capture one tonne of CO_2 at node n, step p
Capture efficiency	$\lambda_{n,p}$	$n \in N^c$ $p \in P$	Capture efficiency at node n, step p
Amount of emissions of plants (tCO_2/year)	$Q_{n,p}$	$n \in N^c$ $p \in P$	Amount of CO_2 emitted at node *n*, step *p* per year

Electricity carbon intensity (tCO_2/ kWh)	Φ		Amount of CO_2 emitted per one unit of electricity consumed
Electricity consumed per unit of CO_2 captured/stored (kWh/year)	α_n^c, α_n^s	n $\in N^c$, $n \in N^s$	Amount of electricity consumed to capture/store one tonne of CO_2 at node n
Unitary storage cost (€/tCO_2)	USC_n	$n \in N^s$	Cost of storing one tonne of CO_2 at node n
Capacity of storage site (tCO_2/year)	S_n	$n \in N^s$	
Unitary transport cost of pipeline (€/tCO_2/km)	UTC_z^{pipe}	$z \in Z^{pipe}$	Unitary cost of transporting CO_2 via pipeline per unit of CO_2 per km subject to size of pipeline
Unitary transport cost of ship - slope (€/tCO_2/km)	$UTC_z^{ship,s}$	$z \in Z^{ship}$	Slope coefficient of unitary cost of transporting CO_2 via ship per unit of CO_2 per km subject to size of ship
Unitary transport cost of ship - intercept (€/tCO_2)	$UTC_z^{ship,i}$	$z \in Z^{ship}$	Intercept coefficient of unitary cost of transporting CO_2 via ship per unit of CO_2 subject to size of ship
Whether distance by truck is within distance range d	$k_{n,n',d}$	$n, n' \in N$ $d = \{d_{1-2}\}$	1: Distance by truck from node n to n' is within d; 0: otherwise
Node distance (km)	$D_{n,n',b}$	$n, n' \in N$ $b \in B$	Distance by transport technology b from node n to n'
Terrain factor	β		

Loss of CO_2 during transporting (tCO_2/km)	θ_b	$b \in B$	The loss of CO_2 per km when transported via transport technology b
Electricity consumed for conditioning (kWh/tCO_2)	$\tau 1, \psi 1, \tau 2, \psi 2$		Amount of electricity required to condition one tonne of CO_2
Emissions of transport technology (tCO_2/tCO_2/km)	$\mu_{1,b}, \mu_{2,b}$		Direct and indirect emissions of transport technology b per unit of CO_2 transported per km

Table 4.9. Input data of the model

4.3.2. Decision variables

Decision variables of a MILP model can be either binary or continuous variables. Our model includes both of them. The binary variables reflect the investment decisions, which determine whether a capture facility is installed at a node, or whether a transport mode is implemented to connect two nodes. The binary variables can take 0 or 1 values, of which 0 means no and 1 is yes. The continuous variables mainly express the operational decisions of the model, such as the volume of CO_2 captured or stored at each node, or the amount of CO_2 transferred between two nodes. The continuous variables in this model can only take non-negative values. The detailed description of each variable can be seen in Table 4.10 below.

Type	Name	Variable	Condition	Description
Binary variable	Installation of CO_2 capture plant	$m_{n,p}$	$n \in N^c$ $p \in P$	1: capture plant is installed at node *n*, step *p*; 0: otherwise
	Installation of CO_2 transport technology from node *n* to *n'*	$y_{n,n',b,z}$	*n, n'* ∈ *N* $b \in B$ $z \in Z^b$	1: transport technology *b* with size *z* is installed from node *n* to *n'*; 0: otherwise
Continuous	Amount of CO_2	$C_{n,p}$	$n \in N^c$	Amount of CO_2

variable	captured at plants (tCO_2/year)		$p \in P$	captured at node *n*, step *p*
	Electricity consumed for capture (kWh/year)	$E^{c}_{n,p}$	$n \in N^{c}$ $p \in P$	Amount of electricity consumed to capture CO_2 at node *n*, step *p*
	Electricity consumed for storage (kWh/year)	E^{s}_{n}	$n \in N^{s}$	Amount of electricity consumed to store CO_2 at node *n*
	Amount of CO_2 stored at storage sites (tCO_2/year)	O_n	$n \in N^{s}$	Amount of CO_2 stored at storage site *n*
	Flowrate of CO_2 transported from node *n* to *n'* (tCO_2/year)	$F_{n,n',b,z}$	$n, n' \in N$ $b \in B$ $z \in Z^{b}$	Amount of CO_2 transported from node *n* to *n'* by transport technology *b*, size *z*
	Electricity consumed for conditioning from capture plant to transport technology (kWh/year)	V_n	$n \in N$	Amount of electricity consumed to condition CO_2 from capture plant to transport technology at node *n*
	Electricity consumed for conditioning from transport technology b to other transport technology (kWh/year)	L^{b}_{n}	$n \in N$ $b \in B$	Amount of electricity consumed for conditioning when transferring CO_2 from transport technology b to other transport technology
	Product of capture amount	w_n	$n \in N$	

	at node n and whether to install pipeline between n and n’			

Table 4.10. Decision variables of the model

4.3.3. Objective

The objectives of the model are minimizing the total system cost (TC [€/year]) required to install and operate the CO2 supply chain network and maximizing the total avoided CO2 amount (H [tCO2/year]) of the system:

$$Objective = \begin{cases} \min(TC) \\ \max(H) \end{cases} \tag{1}$$

4.3.3.1. Total system cost

The total system cost, expressed by equation (Eq.) (2), includes total capture cost (TCC [€/year]), total transport cost (TTC [€/year]), and total storage cost (TSC [€/year]):

$$TC = TCC + TTC + TSC \tag{2}$$

a. Total capture cost (TCC)

The capture cost is calculated by multiplying the amount of CO2 captured, C [tCO2/year], by the unitary capture cost per tonne of CO2, UCC [€/tCO2]. For all node $n \in N^c$, and $p \in P$, the capture cost at each node, $TCC_{n,p}$, is expressed as:

$$TCC_{n,p} = UCC_{n,p} * C_{n,p}$$

Then, the total capture cost is equal to the sum of all the capture costs at each node $n \in N^c$:

$$TCC = \sum_{n \in N^c} \sum_{p \in P} TCC_{n,p}$$

b. Total transport cost (TTC)

As the model considers three types of transport technologies (pipeline, ship, and truck), the total transport cost consists of three elements: total transport cost of pipeline, TTC^{pipe} [€/tCO2]; total transport cost of ship, TTC^{ship} [€/tCO2]; and total transport cost of truck, TTC^{truck} [€/tCO2]:

$$TTC = TTC^{pipe} + TTC^{ship} + TTC^{truck}$$

Pipeline: Particularly, total pipeline transport cost is computed by considering scale effects over CO_2 amount transported through size z with $z \in Z^{pipe}$:

$$TTC^{pipe} = \sum_{n\in N} \sum_{\substack{n'\in N,\\ n'\neq n}} \sum_{z\in Z^{pipe}} F^{pipe}_{n,n',z} * D^{pipe}_{n,n'} * UTC^{pipe}_{z}$$

where $F^{pipe}_{n,n',z}$ [tCO_2/year] is the flowrate transported by pipeline associated to size z from node n to n', $D^{pipe}_{n,n'}$[km] represents the distance by pipeline between node n and n', whereas UTC^{pipe}_{z} [€/tCO_2/km] is the unitary transport cost of pipeline subject to size z of pipeline.

Ship: Total transport cost of ship depends on transported flowrates and the transport distance via ships through a linear regression function.

$$TTC^{ship} = \sum_{n\in N^h} \sum_{\substack{n'\in N^h,\\ n'\neq n}} \sum_{z\in Z^{ship}} F^{ship}_{n,n',z} * (D^{ship}_{n,n'} * UTC^{ship,s}_{z} + UTC^{ship,i}_{z})$$

where $F^{ship}_{n,n',z}$ [tCO_2/year] represents the flowrate subject to size z shipped from node n to n', $D^{ship}_{n,n'}$[km] is the marine distance between node n and n', while $UTC^{ship,s}_{d}$ [€/tCO_2/km] and $UTC^{ship,i}_{z}$ [€/tCO_2] are slope and intercept coefficients associated with size z.

Truck: Total truck transport cost is particularly given by:

$$TTC^{truck} = \sum_{n\in N} \sum_{\substack{n'\in N,\\ n'\neq n}} \sum_{d\in U} F^{truck}_{n,n'} * D^{truck}_{n,n'} * k_{n,n',d} * UTC^{truck}_{d}$$

where $F^{truck}_{n,n'}$ [tCO_2/year] represents the CO_2 amount transported via trucks from node n to n', $D^{truck}_{n,n'}$[km] is the distance by truck between node n and n', $k_{n,n',d}$ is a parameter indicating whether the truck distance is within the distance range d and UTC^{truck}_{d} [€/tCO_2/km] is the unitary transport cost of truck subject to d.

c. Total storge cost (TSC)

Total storage cost is computed by summing up storage costs at all storage sites n $\in N^s$. The storage cost at each storage node, TSC_n, can be determined from the unitary storage cost, USC [€/tCO_2], and the amount of CO_2 stored at corresponding node, O_n [tCO_2/year]:

$$TSC = \sum_{n\in N^s} TSC_n = \sum_{n\in N^s} USC * O_n$$

4.3.3.2. Total avoided CO2 amount

When operating, the CO_2 supply chain network emits a certain amount of emissions. Hence, the total avoided CO_2 amount of the system, H [tCO_2/year], is the difference between the total stored CO_2 amount, O [tCO_2/year], and the total emissions of the system, K [tCO_2/year], as given below:

$$H = \sum_{n \in N^s} O_n - K$$

The total emissions of the system: The CO_2 network discharges CO_2 emissions through capture, conditioning, transport, and storage processes. For the capture, conditioning and storage processes, CO_2 emissions are emitted owing to electricity consumed for capturing ($E^c_{n,p}$ [kWh/tCO_2]), conditioning (G_n [kWh/tCO2]) and storing (E^s_n [kWh/tCO_2]) CO_2, respectively. Among these, electricity consumed for capture and storage can be derived from the captured and stored CO_2 amount, respectively, while electricity consumed for conditioning is identified to account the contributions of electricity consumed for conditioning from capture sites to transport technologies, V [kWh/tCO_2], and electricity consumed for conditioning between different transport technologies, L^b[kWh/tCO_2]. Electricity consumed for conditioning can be expressed as follows:

$$G_n = V_n + L_n^{pipe} + L_n^{ship} + L_n^{truck}$$

For the transport process, the emitted CO_2 amounts include both direct emissions generated from the CO_2 supply chain network operation and the indirect emissions resulting from the technology installation. Accordingly, the total emissions of the CO_2 network are given by:

$$K = \sum_{n \in N} \sum_{p \in P} \phi * (E^s_n + E^c_{n,p} + G_n) + \sum_{n \in N} \sum_{\substack{n' \in N, \\ n' \neq n}} \sum_{b \in B} \sum_{z \in Z^b} D_{n,n',b} * (\mu_{1,b} * F_{n,n',b,z} + \mu_{2,b} * F^{max}_{n,n',b,z})$$

where ϕ [tCO_2/kwh] is electricity carbon intensity, referring to total CO_2 emissions per unit of electricity consumed, $\mu_{1,b}$[tCO_2/tCO_2/km] represents total direct CO_2 emissions of transport technology b per CO_2 amount transported and distance, and $\mu_{2,b}$[tCO_2/tCO_2/km] is total indirect CO_2 emissions of technology b per maximum admissible flowrate of size z installed for technology b and distance.

4.3.4. Constraint

The optimization problem's constraints include three main aspects: (i) considering operational boundaries and performance of each CCS component, (ii) ensuring CO_2 mass balance and (iii) considering electricity consumed for CO_2 conditioning.

4.3.4.1. Operational boundaries and performance of CCS technologies

a. Capture

Regarding capture technologies, the size of each capture unit must fall within the range of zero (no installation of the unit) to the maximum size achievable when considering the capture efficiency (λ) of the installed capture unit and the CO_2 emissions (Q) from the corresponding plant. For all n ∈ N^c and p ∈ P, this constraint is expressed as follows:

$$0 \leq C_{n,p} \leq \lambda_{n,p} * Q_{n,p} * m_{n,p}$$

In addition, the capture unit's performance is represented by a linear relationship that connects the amount of CO_2 captured (C) from the corresponding plant with the required electricity for the capture unit (E^c). This relationship applies to all n ∈ N^c and p ∈ P:

$$E^c_{n,p} = \alpha^c_{n,p} * C_{n,p}$$

where, $\alpha^c_{n,p}$ represents the conversion efficiency, which measures electricity consumed per unit of CO_2 captured at node n and step p.

b. Transport

For ship and pipeline transport, the flowrate of CO_2 (F) is restricted by both the installed size (F^{max}) and a minimum allowable value (F^{min}). For connections between node n and n' (n, n' ∈ N), by transport technology b ∈ {ship, pipe} with size z ∈ Z^b, this constraint can be expressed as follows:

$$y_{n,n',b,z} * F^{min}_{n,n',b,z} \leq F_{n,n',b,z} \leq y_{n,n',b,z} * F^{max}_{n,n',b,z}$$

For truck transport from node n to n' (n, n' ∈ N), the constraint about the flowrate of CO_2 is:

$$0 \leq F^{truck}_{n,n'} \leq M' * y_{n,n'} * \sum_{d \in U} k_{n,n',d}$$

Here M' = 10 Mt is a big number larger than the upper bound of $F^{truck}_{n,n'}$, and $\sum_d k_{n,n',d}$ represents if the road distance from n to n' is greater than or equal to 100 km. If $\sum_d k_{n,n',d} = 0$, $F^{truck}_{n,n'}$ will also be 0. This is to ensure that truck transport is only used for short distances, specifically distances of less than 100 km.

Besides, to reduce the complexity of the problem and reflect the reality, we limit one CO_2 outlet for each node n (n ∈ N). In other words, there will be a maximum of one connection being installed from node n to all other nodes by all transport modes of all different sizes.

$$\sum_{n\prime \in N} \sum_{b \in B} \sum_{z \in Z^b} y_{n,n',b,z} \leq 1$$

c. Storage

In terms of storage technologies, the amount of CO_2 stored (O) in each sequestration site must vary between 0 (i.e., the storage site is not used) and the total capacity of the basin (S). For all nodes n ∈ N^s, we have:

$$0 \leq O_n \leq S_n$$

Moreover, similar to the capture part, the electricity required for injection (E^s) is correlated with the amount of CO_2 stored (O) through the following linear expression for all nodes n ∈ N^s:

$$E_n^s = \alpha_n^s * O_n$$

Here, α_n^s is the conversion efficiency measuring the energy needed per unit of CO_2 stored at node n. However, in our work, the conversion efficiency is set to be zero for all storage sites. This is because the electricity consumption associated with CO_2 storage is influenced by factors such as pressure and temperature of the incoming connection to the storage location (Becattini et al., 2022) and thus is already accounted for in the electricity consumption for conditioning.

4.3.4.2. Mass balance

For each node n (n ∈ N), the mass balance is achieved by imposing that the incoming quantity of CO_2 is equal to the outgoing quantity. To account for the input terms, the CO_2 captured in node n and the quantity of CO_2 transported to node n from all other nodes by all transport modes of all sizes are taken into account. In contrast, the output terms consider the amount of CO_2 stored in node n and the quantity of CO_2 leaving node n. Overall, the mass balance of CO_2 is expressed as:

$$C_n + \sum_{n\prime \in N} \sum_{b \in B} \sum_{z \in Z^b} F_{n',n,b,z} * (1 - \theta_b * D_{n',n,b}) = O_n + \sum_{n\prime \in N} \sum_{b \in B} \sum_{z \in Z^b} F_{n,n',b,z}$$

Here, the parameter θ_b represents the quantification of CO_2 loss during transportation through transport mode b (b ∈ B), and $D_{n',n,b}$ denotes the distance between node n and node n' (n, n' ∈ N) when utilizing the transport mode b. The

CO_2 loss can be described by the following differential equation:

$$\frac{dF}{dD} = -\theta * F$$

4.3.4.3. Electricity consumed for CO_2 conditioning

The capture and transportation of CO_2 involve various states and varying levels of temperature and pressure. To address this, the electrical energy needed for cooling, compressing and liquefying the CO_2 when it is produced and transported through different transport modes is considered. This process is modeled by considering that at each specific location (node), there are two potential flows of CO_2 that need conditioning. The first flow is the CO_2 captured at that node which needs to be brought to the transport conditions. The second flow is the ingoing CO_2 transported to that node which needs to be brought to the next transport conditions.

a. From capture condition to transport condition

For n ∈ N^c, n' ∈ N and z ∈ Z^{pipe}, the electricity consumed for conditioning from capture condition to transport condition (V) at source n can be expressed as follows:

$$V_n = (\psi_1 - \psi_2) * C_n * \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z} + \psi_2 * C_n \quad (3)$$

where, ψ_1, ψ_2 are parameters representing electricity consumed per unit of CO_2 conditioned from the capture condition to the condition of transport by pipeline and truck respectively. Meanwhile, $\sum_{n'} \sum_z y^{pipe}_{n,n',z}$ indicates whether CO_2 is transported from node n by pipeline.

If $\sum_{n'} \sum_z y^{pipe}_{n,n',z}$ = 1, equation (3) will become $V_n = \psi_1 {}^* C_n$

If $\sum_{n'} \sum_z y^{pipe}_{n,n',z}$ = 0, equation (3) will become $V_n = \psi_2 {}^* C_n$

Even though equation (3) is straightforward and easy to understand, it contains a non-linear term which is $C_n * \sum_{n'} \sum_z y^{pipe}_{n,n',z}$. Thus, by adding an additional decision variable w_n ($w_n = C_n * \sum_{n'} \sum_z y^{pipe}_{n,n',z}$), equation (3) can be transformed into three constraints as below to avoid nonlinearity:

$$V_n = (\psi_1 - \psi_2) * w_n + \psi_2 * C_n$$

$$w_n \le M * \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z}$$

$$w_n \le C_n$$

$$w_n + M * \left(1 - \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z}\right) \geq C_n$$

Here, M = 2 billion kwh is a big value larger than the upper bound of the electricity consumed for conditioning CO_2 in any case.

b. From pipeline to other transport technologies

For n ∈ N^c, n' ∈ N and z ∈ Z^{pipe}, we can express the electricity consumed for conditioning CO_2 transported from pipeline to other transport technologies as follows:

$$L^{pipe}_n = \sum_{n' \in N} \sum_{z \in Z^b} F^{pipe}_{n',n,z} * \left(1 - \theta_{pipe} * D_{n',n,pipe}\right) * \tau_1 * (1 - \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z}) \quad (4)$$

Here, parameter τ_1 represents electricity consumed per unit of CO_2 conditioned from pipeline transport to ship or truck transport, and $\sum_{n'} \sum_z F^{pipe}_{n',n,z} * \left(1 - \theta_{pipe} * D_{n',n,pipe}\right)$ is the CO_2 transported to node n by pipeline after deducting the CO_2 lost during transportation.

If $\sum_{n'} \sum_z y^{pipe}_{n,n',z}$ = 1, equation (4) will become $L^{pipe}_n = 0$

This is because from node n, CO_2 will continue to be transported by pipeline and thus there is no need for conditioning from pipeline to other transport technologies.

If $\sum_{n'} \sum_z y^{pipe}_{n,n',z}$ = 0, equation (4) will become:

$$L^{pipe}_n = \sum_{n'} \sum_{z} F^{pipe}_{n',n,z} * \left(1 - \theta_{pipe} * D_{n',n,pipe}\right) * \tau_1$$

However, equation (4) is a non-linear constraint. Thus, we recast it as three linear constraints as below:

$$L^{pipe}_n \leq M * (1 - \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z})$$

$$L^{pipe}_n \leq \sum_{n' \in N} \sum_{z \in Z^b} F^{pipe}_{n',n,z} * \left(1 - \theta_{pipe} * D_{n',n,pipe}\right) * \tau_1$$

$$L^{pipe}_n + M * \sum_{n' \in N} \sum_{z \in Z^b} y^{pipe}_{n,n',z} \geq \sum_{n' \in N} \sum_{z \in Z^b} F^{pipe}_{n',n,z} * \left(1 - \theta_{pipe} * D_{n',n,pipe}\right) * \tau_1$$

c. From ship to other transport technologies

With the same logic as the previous part, we can express the electricity consumed for conditioning CO_2 from ship to other transport technologies through a non-linear constraint. For n, n’ ∈ N and z ∈ Z^{ship}, we have:

$$L_n^{ship} = \sum_{n' \in N} \sum_{z \in Z^b} F_{n',n,z}^{ship} * \left(1 - \theta_{ship} * D_{n',n,ship}\right) * \tau_2 * (1 - \sum_{n' \in N} \sum_{z \in Z^b} y_{n,n',z}^{ship/truck})$$

Here, parameter τ_1 represents electricity consumed per unit of CO_2 conditioned from ship or truck transport to pipeline transport.

This non-linear constraint can be modeled via three linear constraints:

$$L_n^{ship} \leq M * (1 - \sum_{n' \in N} \sum_{z \in Z^b} y_{n,n',z}^{ship/truck})$$

$$L_n^{ship} \leq \sum_{n' \in N} \sum_{z \in Z^b} F_{n',n,z}^{ship} * \left(1 - \theta_{ship} * D_{n',n,ship}\right) * \tau_2$$

$$L_n^{ship} + M * \sum_{n' \in N} \sum_{z \in Z^b} y_{n,n',z}^{ship/truck} \geq \sum_{n' \in N} \sum_{z \in Z^b} F_{n',n,z}^{ship} * \left(1 - \theta_{ship} * D_{n',n,ship}\right) * \tau_2$$

d. From truck to other transport technologies

Similarly, for n, n’ ∈ N and z ∈ Z^{ship}, we can model constraints for this part as below:

$$L_n^{truck} \leq M * (1 - \sum_{n' \in N} \sum_{z \in Z^b} y_{n,n',z}^{ship/truck})$$

$$L_n^{truck} \leq \sum_{n' \in N} F_{n',n}^{truck} * \left(1 - \theta_{truck} * D_{n',n,truck}\right) * \tau_2$$

$$L_n^{truck} + M * \sum_{n' \in N} \sum_{z \in Z^b} y_{n,n',z}^{ship/truck} \geq \sum_{n' \in N} F_{n',n}^{truck} * \left(1 - \theta_{truck} * D_{n',n,truck}\right) * \tau_2$$

5. Result and analysis

5.1. Pareto curve and scenario summary

In our study, the epsilon-constraint (ε-constrain) method was utilized to conduct bi-objective optimization. In this method, one objective is selected to be optimized by the optimizer, while the other objective is constrained to specific values. This constraint is defined using a scalar parameter called ε, which determines the allowable deviation from the optimum value for the constrained objective. By systematically varying the value of ε, the optimizer generates a series of solutions that lie along the Pareto curve, also known as the Pareto frontier or Pareto set. The Pareto curve represents a sequence of global optimum solutions where no solution can be improved in one objective without sacrificing performance in another objective. The Pareto curve helps in visualizing different levels of compromise between objectives, providing a range of solutions that decision-makers can choose from based on their preferences and priorities. (Parvizi et al., 2015)

For our problem, we applied the ε-constrain method by setting the objective function as minimizing the total cost of the network and constraining the total avoided CO_2 to specific values corresponding to different targets for CO_2 emissions reduction, ranging from no amount of CO_2 being avoided to maximizing the amount of CO_2 avoided. As a result, a Pareto curve has been achieved (Figure 5.1).

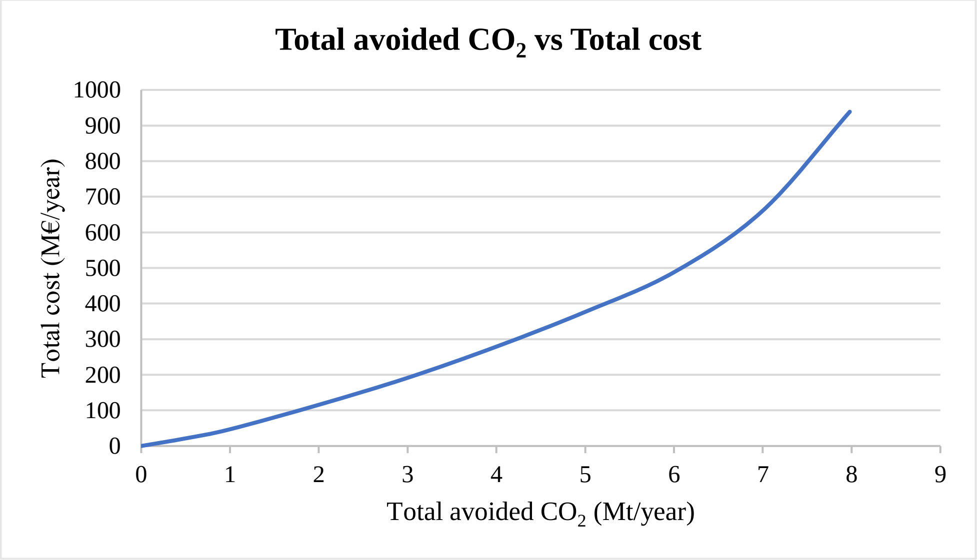


Figure 5.1. Pareto curve representing trade-offs between total avoided CO_2 and total cost

The Pareto curve represents the set of optimal CCS supply chain designs, highlighting the trade-offs between reducing CO2 emissions and bearing higher costs. Each design is independent and optimized without considering the others. The two extreme points of the Pareto curve correspond to two designs: one where there are no changes, indicating total avoided CO_2 and total cost of zero, and another design where all CO_2 emissions from twenty sources are captured, resulting in a maximum total avoided CO_2 of 7.98 Mt/year and a maximum cost of 938.67 M€/year.

In order to derive meaningful insights, we chose nine Pareto-optimal CCS supply chain configurations corresponding to nine different scenarios of total avoided CO_2 for further investigation and analysis. Description of these scenarios and the computational results when running them are summarized in Table 5.1.

Name	**Total avoided CO_2 (Mt/year)**	**Computational results (*)**	
		Optimization gap (%)	**Running time (seconds)**
Scenario 1	0.5	0	0.4
Scenario 2	1	0	1.75
Scenario 3	2	0.9432	27.35
Scenario 4	3	0.9698	35.81
Scenario 5	4	0.9638	51.05
Scenario 6	5	0.9834	396.77
Scenario 7	6	0.9977	4843.03
Scenario 8	7	0.9992	7004.69
Scenario 9	Max (7.98)	0.9995	14389.95

***(*)** The model was run on LAPTOP-VT902MH9, processor: 11th Gen Intel(R) Core(TM) i5-1135G7 @ 2.40GHz 2.42 GHz, installed RAM: 8GB*

Table 5.1. Summary of studied scenarios and computational results

In this section, we also illustrate the resulting CCS supply chain network for five typical scenarios which are scenarios 2, 5, 6, 8 and 9 in Figure 5.2. The schematic representation shown in this figure depicts the structural changes of the CCS network as the quantity of avoided CO_2 progressively grows across the different designs, starting from scenarios 2 and 5, advancing to scenarios 6, 8 and finally scenario 9.

5.2. Scenario analysis

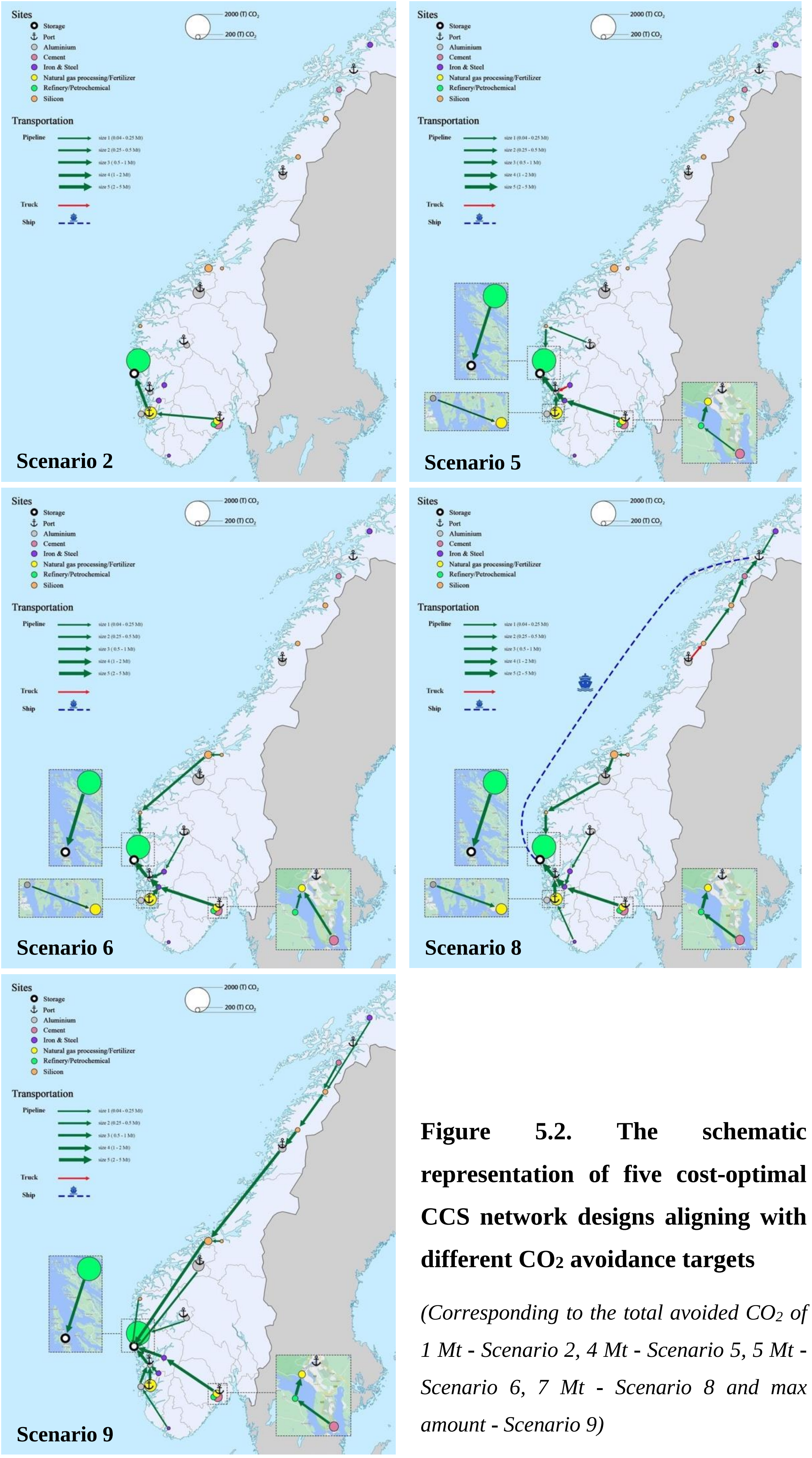


Figure 5.2. The schematic representation of five cost-optimal CCS network designs aligning with different CO_2 avoidance targets

(Corresponding to the total avoided CO_2 of 1 Mt - Scenario 2, 4 Mt - Scenario 5, 5 Mt - Scenario 6, 7 Mt - Scenario 8 and max amount - Scenario 9)

5.2.1. Resulting economics

The objective in each scenario is to minimize the total cost TC (M€/year) of the CCS supply chain network to achieve a specific level of the avoided CO_2 corresponding to that scenario. Table 5.2 presents an overview of the economic results for all nine studied scenarios. In addition to TC, TCC, TTC, and TSC, it also shows the total specific cost, referred to as the cost of avoided carbon CAC [€/tCO_2], as well as specific costs of capture, transport and storage (the yearly costs for capturing, transporting and storing CO_2 with respect to the yearly amount of CO_2 avoided). CAC is calculated by dividing total cost TC [M€/year] by the avoided CO_2 [Mt/year]. We chose to investigate CAC instead of the cost of stored carbon CSC [€/tCO_2] as CAC takes into account all the emissions generated by the supply chain network, which are overlooked in the CSC indicator.

Scenario name	Avoided CO2 (Mt/year)	TC (M€/year)	TCC (M€/year)	TTC (M€/year)	TSC (M€/year)	CAC (€/tCO2)	TCC/CO2 avoided (€/tCO2)	TTC/CO2 avoided (€/tCO2)	TSC/CO2 avoided (€/tCO2)
Scenario 1	0.5	21.4	6.4	5.0	10.0	42.9	12.7	10.1	20.1
Scenario 2	1	46.9	12.7	14.1	20.1	46.9	12.7	14.1	20.1
Scenario 3	2	115.7	56.9	18.7	40.1	57.9	28.4	9.4	20.1
Scenario 4	3	191.5	108.8	22.5	60.2	63.8	36.3	7.5	20.1
Scenario 5	4	279.0	168.2	30.5	80.3	69.8	42.0	7.6	20.1
Scenario 6	5	376.6	227.2	49.0	100.4	75.3	45.4	9.8	20.1
Scenario 7	6	487.9	285.6	81.7	120.7	81.3	47.6	13.6	20.1
Scenario 8	7	660.9	411.4	108.4	141.1	94.4	58.8	15.5	20.2
Scenario 9	7.98	938.7	614.2	164.2	160.3	117.6	77.0	20.6	20.1

Table 5.2. Cost results for all studied scenarios

From Table 5.2 and Figure 5.3, we can see that the overall costs of the supply chains rise in relation to the level of the avoided CO_2. Beginning at a total cost of 21.4 M€/year for scenario 1, where the avoided CO_2 is 0.5 Mt/year, equivalent to 5% of total emissions from all considered sources, it escalates to 938.7 M€/year for scenario 9, where the avoided CO_2 is maximized and corresponds to 83% of the total emissions. The maximum avoided CO_2 does not reach 100% of the total emissions due to the capture efficiencies being less than 100%, the CO_2 losses during transportation and the emissions emitted from the operation of the CCS supply chain. It can also be observed from Figure 5.2 that the total cost increases gradually from scenario 1 to scenario 6 before rising more rapidly from scenario 7 to scenario 9.

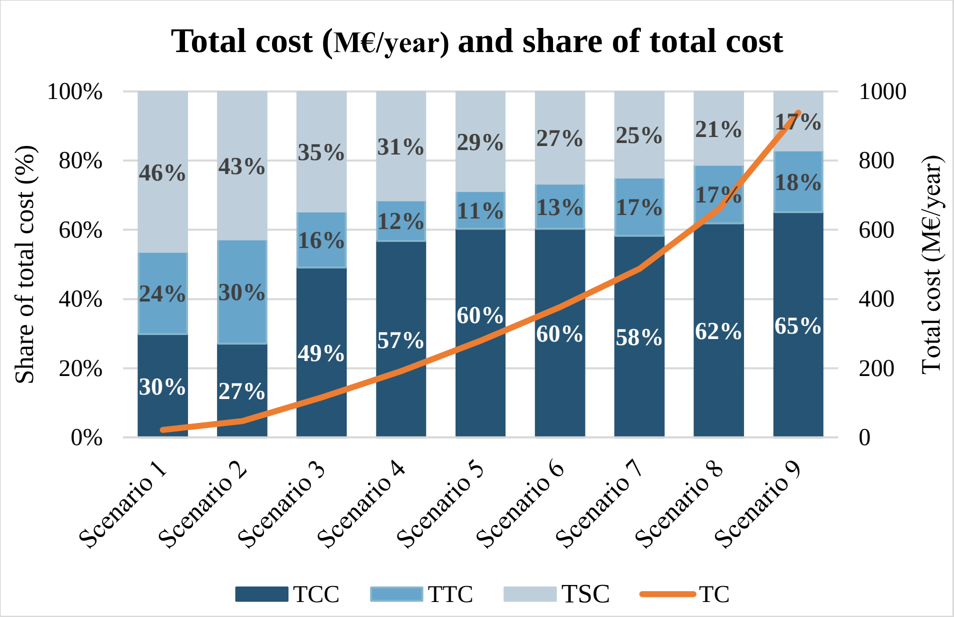


Figure 5.3. Total cost of supply chain designs and share of total costs among capture, transport and storage

As the target for reducing CO_2 emissions becomes higher, the cost components of the total cost, including the costs of capture (TCC), transport (TTC) and storage (TSC), also increase. Regarding their contributions to the total cost, different patterns are observed for the first two scenarios, the next five scenarios and the last scenario, as illustrated in Figure 5.3. In scenario 1, the storage cost constitutes the largest portion of the total cost at 46%, followed by the capture cost at 30% and the transport cost at 24%. Moving to scenario 2, the storage cost remains the largest contributor at 43%, while the transport cost becomes the second largest at 30%, and the capture cost follows with 27%. As the carbon reduction target becomes more stringent in the next five scenarios, the capture cost becomes the dominant factor, ranging from 49% to 62%. The storage cost comes in second, although decreasing gradually from 35% in scenario 3 to 21% in scenario 8, while the transport cost represents the smallest fraction of the total cost. However, in scenario 9, where the avoided CO_2 is maximized, the percentage of transport cost surpasses that of storage cost, and the capture cost still accounts for the largest share at 65%. On average, the capture cost makes up the largest portion of the total cost (52%), followed by the storage cost (30%) and the transport cost (17%).

When it comes to the cost of avoided carbon CAC [€/tCO_2], Table 5.2 and Figure 5.4 demonstrate that it progressively increases in relation to the level of avoided carbon emissions: starting from 42.9 €/tCO_2 in scenario 1, it reaches 117.6 €/tCO_2 in scenario 9. This pattern indicates that the expense of preventing a fixed amount of CO_2 becomes higher as the reduction target becomes more stringent. Additionally, Figure 5.4 illustrates that the increment in the total specific cost CAC primarily stems from the specific capture cost. The specific storage cost remains unchanged while the specific transport cost shows moderate variation across scenarios. Evaluating the cost of CO_2 avoidance also provides valuable insights into a potential carbon tax in Norway. For example, to avoid 5 $MtCO_2$/year, a carbon tax should be about 75.3 €/tCO_2 to offset the investment and operation costs associated with the CCS system. Preventing the release of the remaining portion of CO_2 into the atmosphere would result in an escalation of the carbon tax, surpassing the threshold of 100 €/tCO_2.

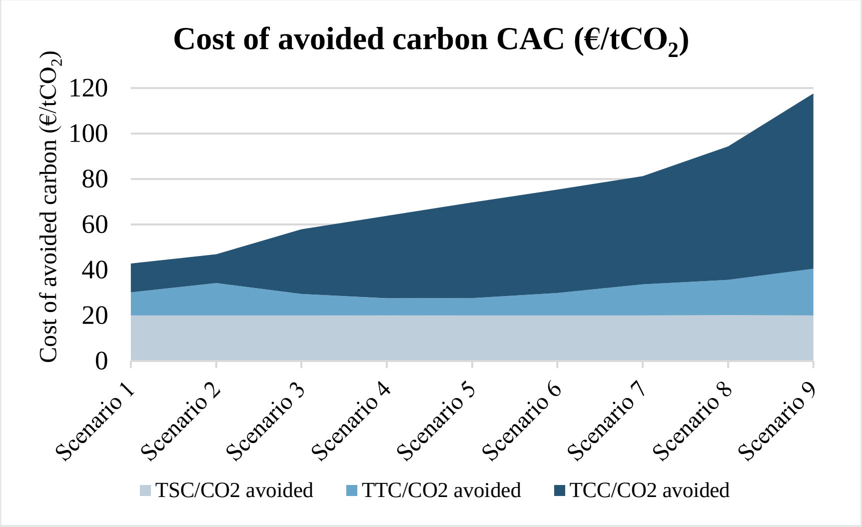


Figure 5.4. Cost of avoided carbon and its distribution among capture, transport and storage

5.2.2. Emissions of the system

While the operation of the CCS supply chain network leads to additional emissions, these emissions amount to less than 1% of the total CO_2 stored in each of the nine scenarios. Generally, the total emissions of the system rise with the increase of the emissions reduction target, as shown in Figure 5.5. Starting from a total emissions level of 1792 tCO_2/year in scenario 1, it increases linearly to 18989 tCO_2/year in scenario 6. However, the growth becomes more dramatic in scenario 7 and 8, reaching 33326 and 53523 tCO_2/year, respectively, when ship is utilized to transport CO_2 captured from the northern part of the system. An exception to this trend can be seen when moving from scenario 8 to scenario 9. In scenario 9, the system exclusively exploits pipeline technology to transmit the captured CO_2, making the total system emissions lower than scenarios involving the ship transport.

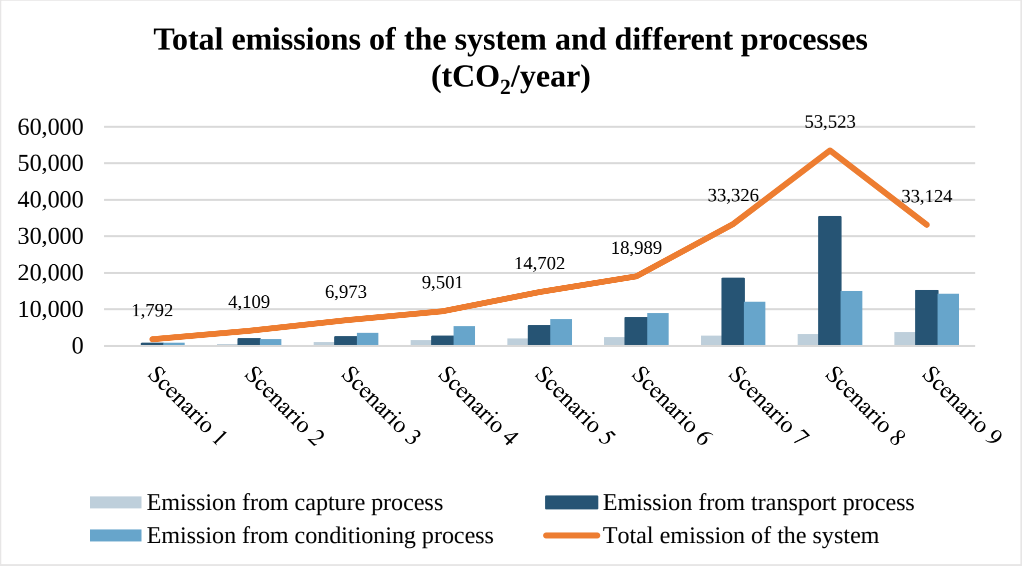


Figure 5.5. Total emissions of the system and different processes

Taking a closer look at the emissions from different processes, while the same pattern as the total emissions of the system can be observed for the emissions from the transport and conditioning processes, the emissions from the capture process rise steadily throughout nine scenarios. It is noteworthy that the capture process consistently emits the lowest amounts of emissions among the three contributions, accounting for less than 17% of the total system emissions (Figure 5.6). The conditioning process emerges as the largest emitter in the first six scenarios, while the transport process generates the highest emissions in the last three scenarios. The use of ship transport, longer travel distances to capture at plants in the northern part, and the absence of requirement to adjust condition of CO_2 transported via different transport technologies in Scenario 9 contribute to the change in the rankings of the emissions from the transport process and conditioning process.

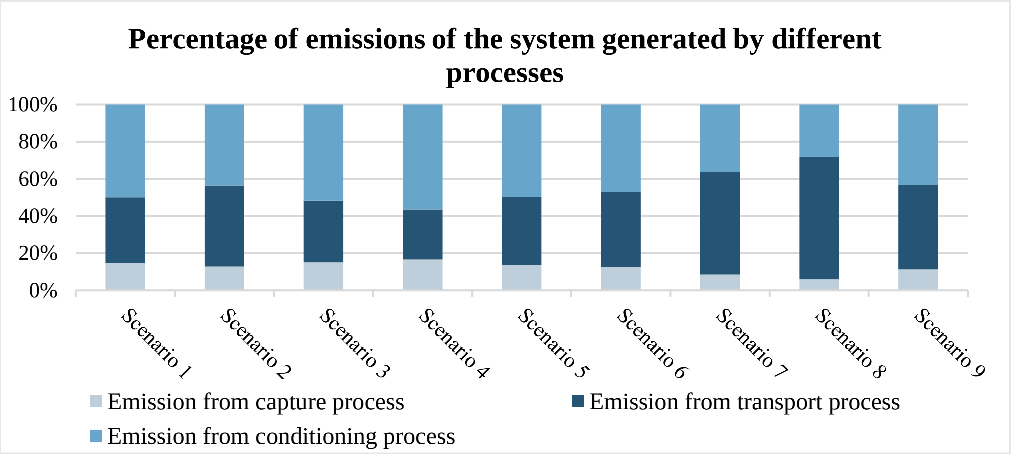


Figure 5.6. Emissions of the system by different processes

5.2.3. Components of CCS supply chain

5.2.3.1. Capture and storage processes

Table 5.3 presents the captured and stored amounts of CO_2 in all studied scenarios. The captured amount is always greater than the stored amount due to losses during transportation, and the stored amount is greater than the avoided CO_2 due to the emissions generated by the supply chain. In our study, it is assumed that LUNA and Smeaheia use the same receiving terminals as Northern Light. Besides, the combined capacity of these three storage sites reaches up to 30 Mt/year, while the total emissions from the selected sources amount to just 9.69 Mt/year, meaning that there is no need for concern regarding the storage capacity. Thus, the selection of storage sites and the decision of the amount stored at each site become irrelevant. In this part, we will mainly analyze the results related to the capture process.

Scenario name	Captured amount (tCO2/year)	Stored amount (tCO2/year)	Difference/Loss (tCO2/year)
Scenario 1	501,954	501,792	162
Scenario 2	1,004,583	1,004,109	474
Scenario 3	2,007,635	2,006,973	662
Scenario 4	3,010,321	3,009,501	821
Scenario 5	4,016,009	4,014,699	1310
Scenario 6	5,021,118	5,018,986	2131
Scenario 7	6,036,350	6,033,319	3032
Scenario 8	7,058,024	7,053,516	4508
Scenario 9	8,018,292	8,012,761	5531

Table 5.3. Captured amount and stored amount in all studied scenarios

The increase in CO_2 avoidance is mainly achieved by installing more CO_2 capture units, as can be seen in Figure 5.2 and Figure 5.7. In scenario 1, only one capture unit is installed, whereas scenario 9 requires the installation of all 25 capture units to meet the emissions target. It is worth noting that there can be more capture units than the number of sources as each aluminum plant can accommodate two capture units for the refining and smelting steps.

As previously stated, the rise in CAC is mainly attributed to the increase in the specific capture cost. Figure 5.7 demonstrates that the specific capture cost has its minimum value at 12.7 €/tCO$_2$ in scenarios 1 and 2, then increases sharply when moving from scenario 2 to scenario 3. Subsequently, the rate of increase slows down before becoming significant again from scenario 7 to scenario 9. In scenario 9, the specific capture cost reaches its highest value at around 77 €/tCO$_2$. This trend can be well explained by Figure 5.8. For scenarios 1 and 2, the solver can still satisfy the requirements about avoided CO$_2$ by using only natural gas processing and fertilizer plants whose unitary capture cost is the lowest (12.7 €/tCO$_2$). Afterwards, from scenario 3 to scenario 7, it requires the deployment of more expensive capture facilities at other sectors to fulfill the growing CO$_2$ abatement targets. Finally, in scenarios 8 and 9, capture units at aluminium smelters which are characterized by the highest unitary capture cost (211.2 €/tCO$_2$) are installed, leading to a significant increase in the overall specific capture cost and CAC.

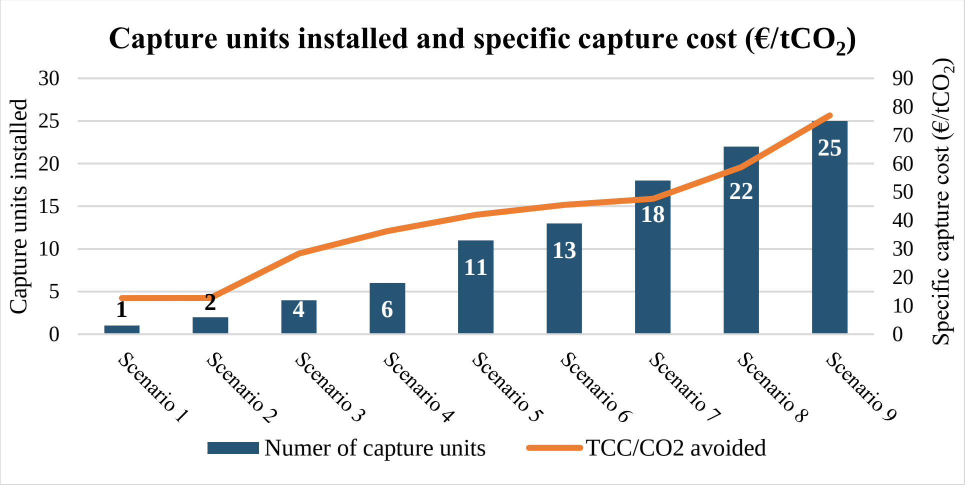


Figure 5.7. The number of capture units installed and the specific capture cost with respect to avoided CO$_2$

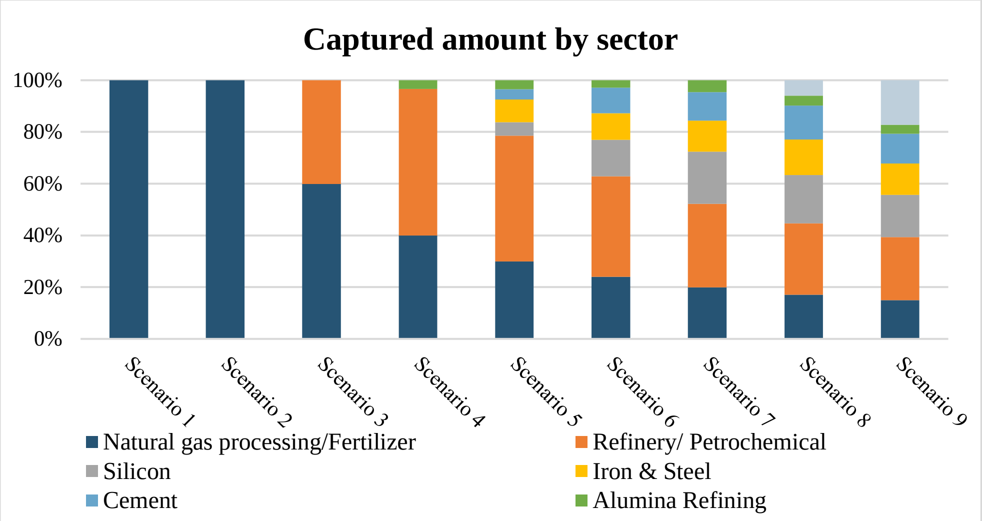


Figure 5.8. The amount of CO$_2$ captured by sector

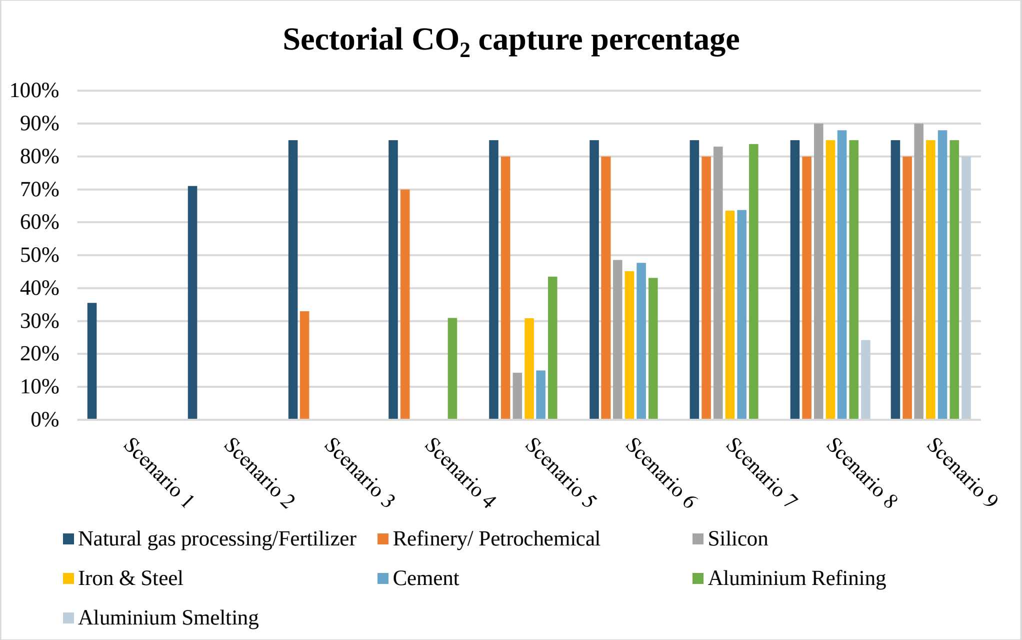


Figure 5.9. Sectorial CO$_2$ capture percentage: Proportion of captured CO$_2$ compared to total sector emissions

A detailed analysis on the capture distribution among sectors shown in Figure 5.8 and the sectorial CO$_2$ capture percentage (the proportion of captured CO$_2$ in a sector compared to total emissions from that sector) shown in Figure 5.9 reveals more insights into the selection of carbon sources. The deployment of capture units in Gassco AS Kårstø processing plant and Yara Porsgrunn takes precedence due to their advantageous unitary capture cost. From scenario 3, as the sectorial capture percentage is pushed towards the 85% limit of capture efficiency for these two plants, refinery/petrochemical plants start to be exploited. Despite the higher unitary capture cost of petroleum refinery/petrochemical plants compared to silicon factories and alumina refineries, they are preferred for several reasons. Firstly, even though there are only two plants in this sector, they are responsible for the largest share of emissions (25%). The second reason is related to their convenient locations. While Mongstad is a large-scale plant located in close proximity to the storage sites, Ineos Rafnes is situated near Yara Porsgrunn, facilitating the establishment of a cost-effective network in the Southern area.

From scenario 5 to scenario 7, capture units are installed in all sectors except for aluminium smelters given their high cost. Regarding alumina refineries, although their unitary capture cost is the second lowest, they only account for 3% of the total emissions from the studied sources. Thus, they are often grouped with other nearby sources for CO$_2$ transportation, aiming to reduce costs. In scenario 7, the CO$_2$

capture percentages for natural gas processing/fertilizer, refinery/petrochemical and alumina refining sectors reach their maximum levels, which are their capture rates. However, for other sectors, there are some plants located in the far North that remain unused in scenario 7. As we move towards scenario 9, CO_2 emissions need to be captured from all plants across all sectors to meet the CO_2 avoidance target.

Analyzing the changes in the supply chain networks from scenario 2 to scenario 5, scenario 6 and scenario 8 illustrated in Figure 5.2, we can see the development of different clusters of sources as the mitigation target intensifies. In scenario 2, CO_2 is transported from Yara Porsgrunn to Gassco AS Kårstø before onward transportation to the storage site. As we progress to scenario 5 and 6, we observe the establishment of clusters centered around these two plants. In the Southern area, Yara Porsgrunn, Heidelberg materials Brevik and Ineos Rafnes are interconnected through a shared pipeline infrastructure for transporting CO_2 to another capture site outside of the region. Meanwhile, in the Southwestern and Western regions, Gassco AS Kårstø, Hydro Aluminum Karmøy, Sør-Norge Aluminium, Eramet Norway Sauda and Eramet Titanium & Iron form another cluster to optimize the transportation of captured CO_2 for storage.

Finally, in scenario 8, the formation of clusters within central and western Norway is observed. This includes the integration of Elkem Thamshavn, Wacker Chemicals Norway and Hydro Aluminum Sunndal into a cohesive cluster of sources. Additionally, a cluster emerges in the Northern part of Norway. The CO_2 emissions generated by Finnfjord, Norcem Kjøpsvik, Elkem Salten, Elkem Rana and Alcoa Norway AS Mosjøen are collected and transported to the Port of Narvik before being transferred to the storage sites by ship. These developed clusters allow for the utilization of shared infrastructure, such as pipelines and ships, and provide opportunities to capture from small sources such as alumina refineries, which ultimately reduces costs and environmental impacts for CCS projects.

5.2.3.2. Transport process

In this part, the results related to transport network, economic performance and environmental impact of each transport technology will be discussed.

a. Transport network

The results reveal that more intricate transport networks are developed to align with stricter emissions targets. Specifically, the total length of connections installed, and the number of transport routes generally increase for higher emissions requirements, as illustrated in Figure 5.10, although there are exceptions in some scenarios. For the total length of transport connections, beginning at a length of 161 km in scenario 1, it surges to over 2900 km in scenario 9. However, there is a slight decrease in the connection length from scenario 3 (485 km) to scenario 4 (483 km) since one truck connection between Ineos Rafnes and Yara Porsgrunn is replaced by the pipeline route when the volume of CO_2 captured becomes bigger. Additionally, the fall in the total connection length can be observed from scenario 8, where there is a ship route, to scenario 9, where only pipeline is used to comply with the highest emissions requirement. This transport mode change also explains for the reduction in the number of transport routes from scenario 8 (21 routes) to scenario 9 (20 routes).

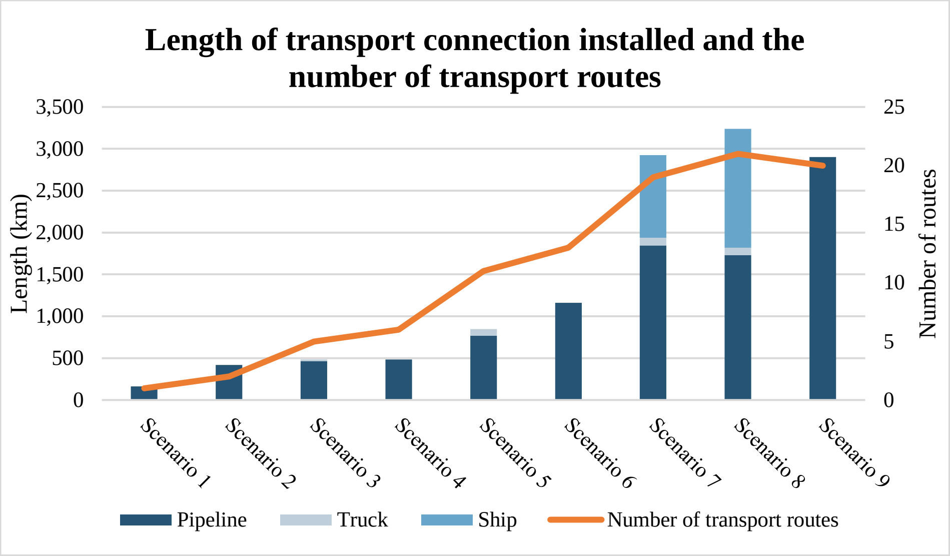


Figure 5.10. Length of transport route installed for each type of transport technology and the number of transport routes

The first transport link is established through a pipeline route connecting Gassco AS Kårstø processing plant with the storage site. Although this plant is not the closest CO_2 source to the storage site, it belongs to the sector having the lowest unitary capture cost and has the shortest distance to the storage site in this sector. Then, the transport configuration is further expanded as avoiding more CO_2 is required. Particularly, the transport connections are initially enlarged to regions near the existing transport infrastructure. For example, in scenario 3, new connection from Ineos Rafnes to Yara Porsgrunn whose CO_2 is already captured in scenario 2 is exploited to take advantage of scale effect of pipeline transport for the outgoing route from Yara Porsgrunn. Later, when the carbon reduction requirement becomes more demanding, connections to more distant parts of the system are considered. For instance, it is not until the target calls for the avoidance of 6 Mt of CO_2 that certain sources in the northern region of Norway are connected to the storage sites.

An important observation is that the resulting systems tend to cluster sources that are geographically close to each other into one source prior to moving to the storage site, causing limited direct connections from capture plants to the storage sites. This approach helps to leverage economies of scale, lowering the total transport cost.

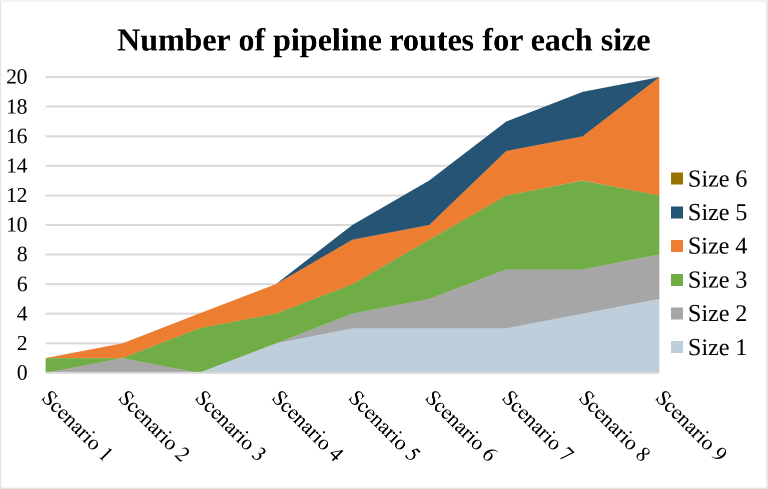


Figure 5.11. Number of pipeline routes per each size

Among the three transport technologies, pipeline is employed most frequently. Pipeline routes cover most of the transport network across nine scenarios. In some scenarios, such as scenarios 1, 2, 4, 6, and 9, the entire network depends on pipeline transport. Additionally, the results show that pipeline transport is installed between two nodes in which the distances are under 420 km. While the biggest size of pipeline, size 6 (5 – 10 Mt), is not operated in any scenario, the sizes under 2 Mt, sizes 1, 2, 3 and 4, are installed the most and size 5 is only considered from scenario 5 to 8 (Figure 5.11).

Truck and ship connections are marginally chosen in the resulting design optimization. For truck transport, it is selected only for small flow rates of CO_2 (less than 60 kt) and short distances where it provides relatively low transport cost. Ship transport, on the other hand, is only employed when the high emissions reduction target requires the system to capture CO_2 from more distant regions. Specifically, ship transport is exploited in scenario 7 and 8 to transport the CO_2 captured from the northern part of the system. In both scenarios, the captured CO_2 is consolidated at one source, particularly the Port of Mosjøen in scenario 7 and the Port of Narvik in scenario 8, before being transported to the storage sites. The ship routes cover distances exceeding 980 km in these cases.

While the combination of long-distance travel and the aggregation of large CO_2 volume can reduce the transport cost for ship, it can also result in a significant increase in the amount of CO_2 lost during transportation. As depicted in Figure 5.12, the CO_2 loss caused by ship transport is over 500 tCO_2/year in scenario 7 and over 1500 tCO_2/year in scenario 8. These losses account for approximately 21.9% and 51.8% of the losses experienced in the pipeline transport, respectively, despite ships carrying less than 1% of the total CO_2 volume transported by pipelines.

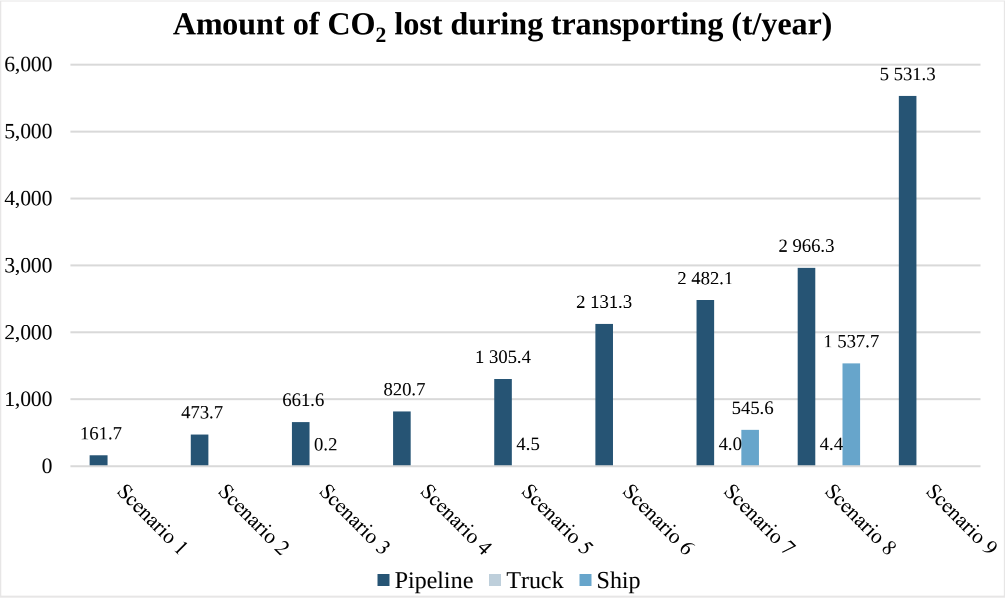


Figure 5.12. Amount of CO_2 lost during transport per each type of transport technology

b. Economic performance

As mentioned earlier, the total transport cost (TTC) of the system increases as the emissions reduction target becomes more stringent. The primary contributor to TTC is due to the pipeline transport cost, always accounting for more than 70% of TTC (Figure 5.13). This is justified by the fact that the transport networks in all nine scenarios are predominantly based on pipeline transport to comply with the cost and emissions objectives (Figure 5.14). When ship transport is employed in scenario 7 and 8, it makes up more than 20% of TTC, despite transporting a significantly lower volume of CO_2 compared to the pipeline transport. The cost of truck transport only represents a limited portion of TTC, under 1.5% (Figure 5.13).

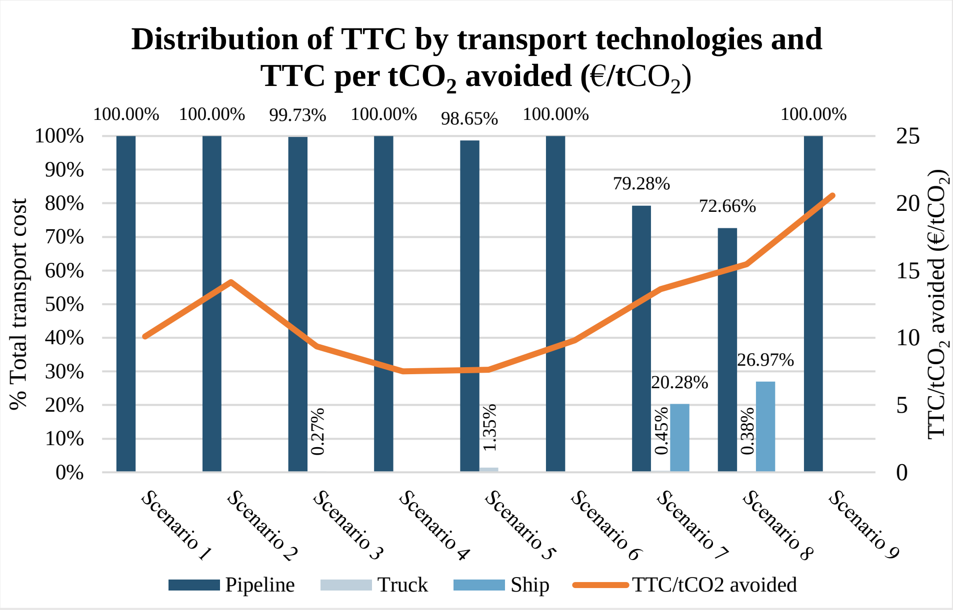


Figure 5.13. Distribution of TTC by transport technologies and TTC per tCO$_2$ avoided

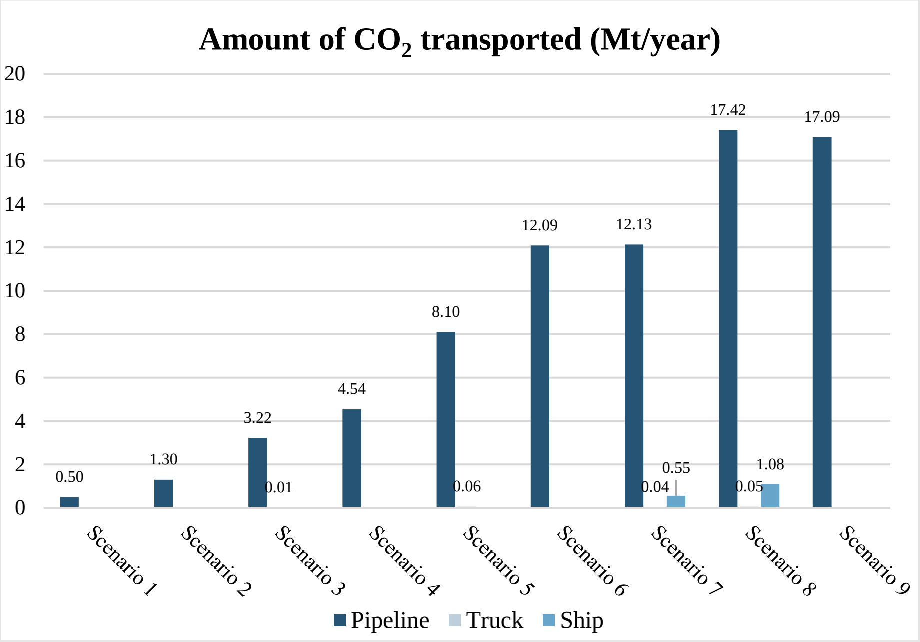


Figure 5.14. Amount of CO$_2$ transported per each transport technology

Additionally, the specific transport cost of the system, derived by dividing the total transport cost by the total amount of avoided CO$_2$ (TTC/Total avoided CO$_2$) [€/tCO$_2$], fluctuates depending on the emissions target (Figure 5.13). Initially, it rises from scenario 1 to scenario 2. In this situation, a relatively high investment cost for pipeline transport is required to transfer a limited amount of CO$_2$ needed to meet the carbon reduction target. Then, with the emergence of economies of scale in the pipeline system when larger volumes of CO_2 are transported, the transport cost per tCO_2 avoided moderately declines from scenario 2 to scenario 5. However, it starts to rise again from scenario 5 to scenario 9. This increase is due to the utilization of ships and by the longer transport routes to connect the northern part of the system to address the more challenging emissions target.

c. Environmental impact

When it comes to environmental impact of transport technology, pipeline transport is the main source of transport-related emissions of the system across most scenarios, except for Scenario 8. This is because pipeline transport handles the majority of the CO_2 amount within the network. While truck transport produces a certain level of CO_2 emissions during operation, ship transport is particularly notable for its remarkably high emissions subject to the amount of CO_2 transported. For example, in scenarios 7 and 8, ship transport transfers small amount of CO_2, but releases emissions that are nearly equal to and more than 2.5 times the emissions generated by the pipeline transport, respectively, as depicted in Figure 5.15, causing a significant increase in the total emissions from the transport process in these scenarios.

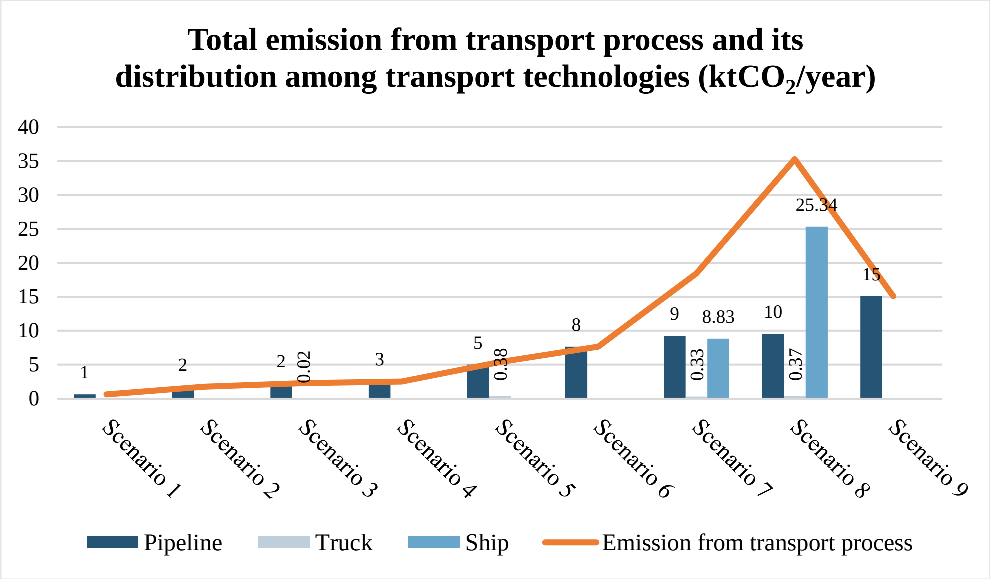


Figure 5.15. Emissions from transport process per each transport technology

The substantial emissions from ship transport can be attributed to the extensive distances it needs to cover to connect capture plants in the north of Norway with the storage sites. Moreover, the consolidation of the captured CO_2 to achieve economies of scale, to some extent, amplifies the indirect emissions associated with the ship transport installation, especially when the gathered volume just approaches the minimum capacity of one ship size. For instance, in scenario 8 (Figure 5.2), all the CO_2 captured from the northern region, amounting to 1.08 Mt, is gathered at the Port of Narvik. Subsequently, a ship of size 3 (1 – 2 Mt) is utilized to transmit the captured CO_2 to the storage site. While this network aids in reducing the ship transport cost, it also expands the indirect emissions of the ship since the indirect emissions of transportation process are influenced by the maximum capacity of a transport technology, which is 2 Mt in this scenario.

The impact of the consolidation on the indirect emissions of transport technology can also explain the change of transport network in scenario 9 which endures the highest emissions target. Unlike the other scenarios which have a maximum of four direct connections to the storage sites, scenario 9 employs six transport routes to connect various nodes directly with the storage sites. In this scenario, besides seeking opportunities to gain benefits from scale effects, the system distributes the captured CO_2 in a manner that maximizes the utilization of transport's capacity. This approach is done to align with both economic and emissions objectives. Consequently, the volumes of CO_2 transported in the direct routes to the storage sites closely reach the maximum capacity of the corresponding pipeline size.

5.3. Sensitivity analysis

In this part, sensitivity analyses will be conducted to thoroughly examine the impacts of four factors on the results of the model: capture efficiency, unitary capture cost of the smelting step in the aluminium sector, the unitary transport cost of truck and the electricity consumed per unit CO_2 captured. For all these analyses, scenario 6 is selected as the reference case due to several reasons. Firstly, the objective of avoiding 5 Mt CO_2 is sufficient to comply with Norway's target of reducing emissions by up to 55% by 2030 compared to the 1990 level (Norwegian Ministry of Climate and Environment, 2021). Secondly, the transportation network in scenario 6 begins to expand to more distant parts of the system and covers more short distances which are potential for truck transport. Finally, although some sources within the aluminium sector have implemented CO_2 capture technologies in scenario 6, these efforts have only focused on the refining steps.

5.3.1. Capture efficiency

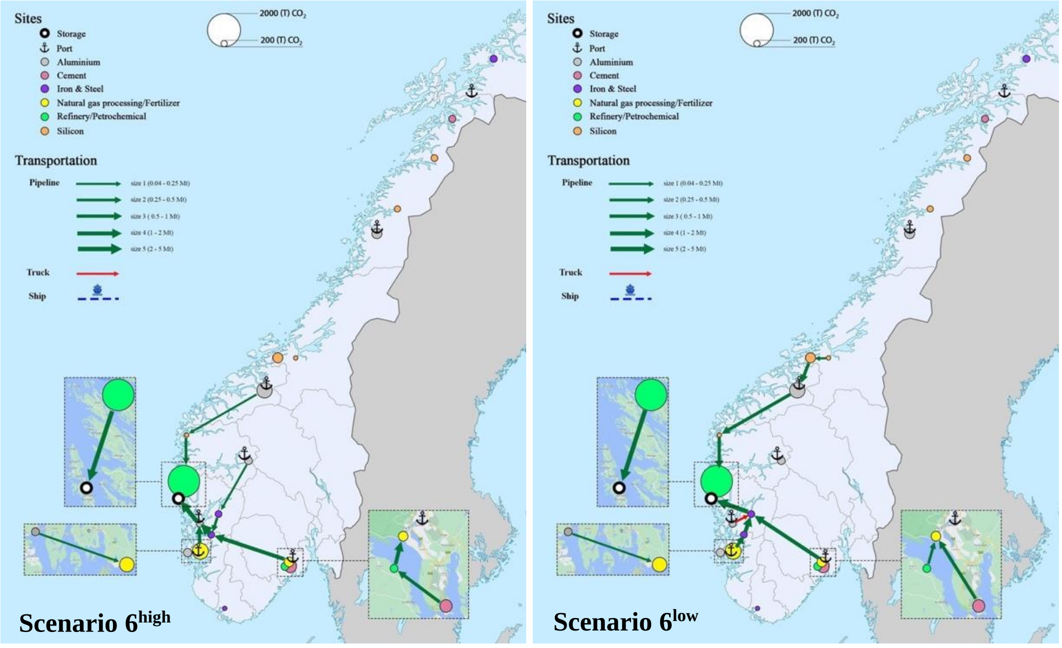
As capture efficiency (λ) is an important parameter in the capture process, we have undertaken a sensitivity analysis to examine its impact on the optimal CCS supply chain network. In this section, we present scenario 6^{high} and scenario 6^{low} which represents scenarios with high capture efficiency (90%) and low capture efficiency (80%) respectively (Table 5.4). The ensuing discussion will focus on comparing the results of these scenarios with the reference case of scenario 6.

Scenario name	Capture efficiency λ (%)						
	Cement	Iron & Steel	Refinery/ Petrochemical	Aluminium		Silicon	Natural gas processing /Fertilizer
				Refining	Smelting		
Scenario 6^{high}	80	80	80	80	80	80	80
Scenario 6 (base case)	88	85	80	85	80	90	85
Scenario 6^{low}	90	90	90	90	90	90	90

Table 5.4. Sensitivity analysis scenarios on capture efficiency *λ* (%)

As can be seen from Figure 5.16, if the capture rate is set to 90% for all sources, several structural changes occur within the CCS system compared to the base case. Firstly, capture units at two silicon plants in the central Norway, namely Elkem Thamshavn and Wacker Chemicals Norway, are no longer needed and replaced by only one capture unit at the nearby Hydro Aluminum Sunndal plant. This can be explained by the fact that a higher capture efficiency ensures a more optimal utilization of CO_2 sources, leading to fewer installations required to achieve the same emissions target. Moreover, in scenario 6^{high}, some modifications have been made compared to the reference case to leverage economies of scale better. For example, in the Southern area, CO_2 emissions from Heidelberg materials Brevik are moved to Ineos Rafnes before being transported onward to Yara Porsgrunn, instead of being directly transported to Yara Porsgrunn as in scenario 6. In addition, in the Southwest area, CO_2 from Gassco AS Kårstø processing plant can be directly transported to Sør-Norge Aluminium without being transferred through Eramet Norway Sauda.

When it comes to scenario 6^{low}, there are also several changes in the resulting optimal CCS supply chain network. Firstly, the capture unit at the refinery in Hydro Aluminum Sunndal plant is used to replace that in Hydro Aluminum Årdal Metallverk. This is because with a capture rate of 80%, the maximum emissions that can be captured from the refinery in Hydro Aluminum Årdal Metallverk are still too low for a cost-effective transportation. Secondly, a truck connection emerges from Sør-Norge Aluminium to Eramet Titanium & Iron as a lower CO_2 amount needs to be transported. Furthermore, in the map area below the storage sites, CO_2 emissions in scenario 6^{low} are gathered at Eramet Titanium & Iron instead of Sør-Norge Aluminium as in scenario 6 before reaching the storage sites.



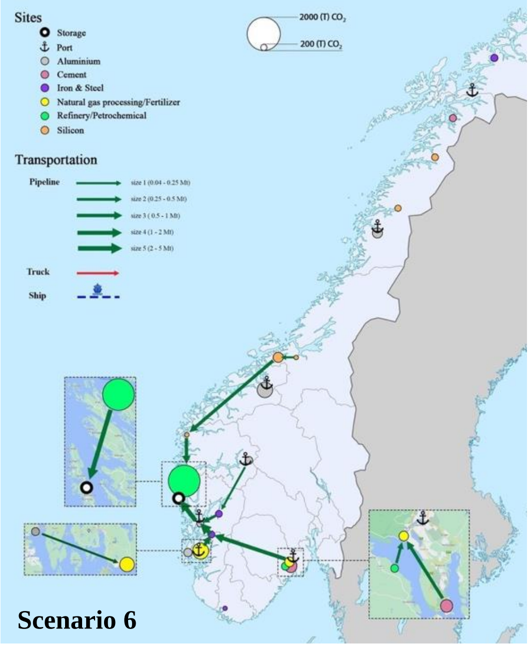


Figure 5.16. The results of sensitivity analysis on capture efficiency regarding the structure of the system

The economic results of scenarios 6^{high} and 6^{low} exhibit the expected outcome, with a respective decrease and increase in total capture and transport costs compared to scenario 6, while total storage cost remains stable (Figure 5.17). As a result, scenario 6^{high} and scenario 6^{low} result in a total cost of 366 M€/year (-11 M€/year relative to scenario 6) and of 383 M€/year (+6 M€/year relative to scenario 6), respectively. Notably, when moving from scenario 6 to scenario 6^{high}, the transport cost decreases considerably by 18.4% thanks to improved utilization of economies of scale in the pipeline infrastructure.

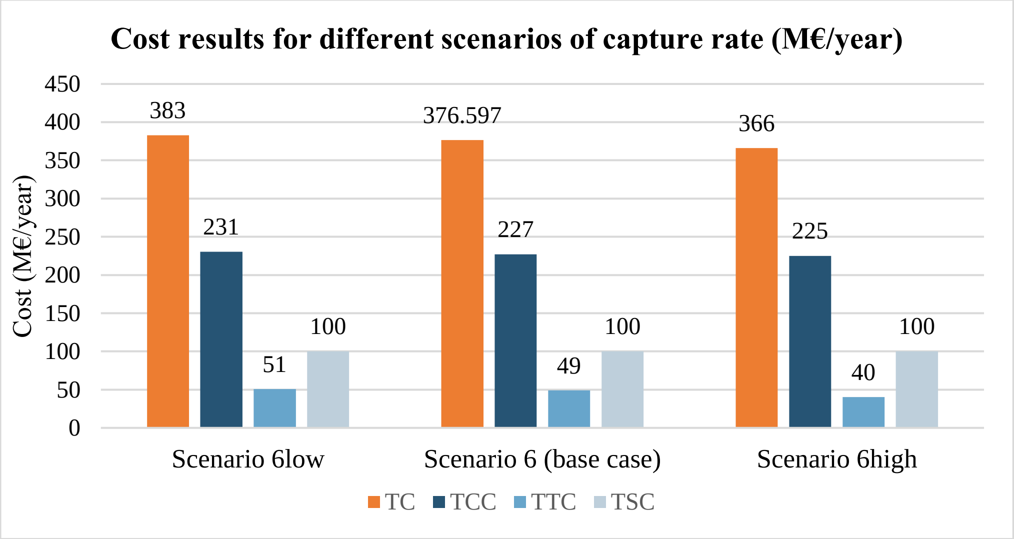


Figure 5.17. Cost results for different scenarios of capture efficiency

The same trend is observed in the total CO_2 emissions of the system (Figure 5.18). As the capture rate is set at 90% for all sources, the overall CO_2 emissions generated by the CCS supply chain network decrease to 17.78 kt/year (-1.21 kt/year relative to scenario 6). By contrast, in the case of an 80% capture rate, the emissions increase to 19.13 kt/year (+0.14 kt/year relative to scenario 6). As a result, with the same target of CO_2 avoidance, scenario 6^{high} requires the lowest amount of CO_2 storage, whereas scenario 6^{low} necessitates the highest among all three scenarios.

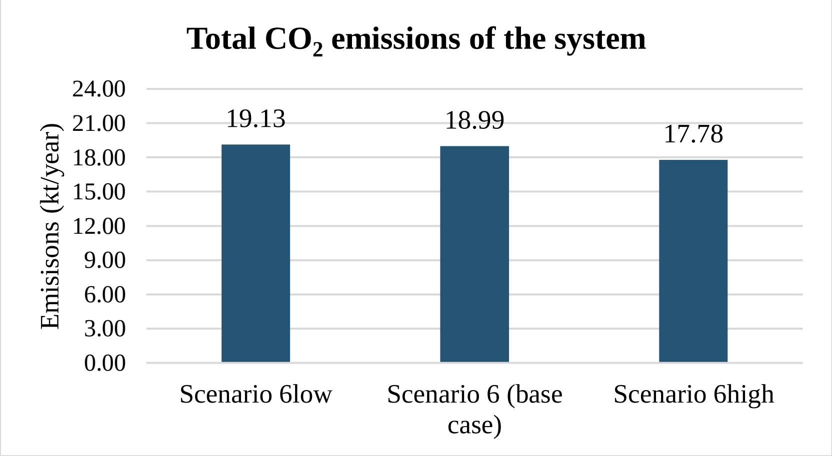


Figure 5.18. Total CO_2 emissions of the systems for different scenarios of capture efficiency

Based on the analysis, we conclude that the CCS supply chain network design in scenario 6 is sensitive to capture efficiency. A higher efficiency leads to a more cost-effective and environmentally friendly network while a lower efficiency has the opposite effect.

5.3.2. Unitary capture cost in aluminium smelters

One of the important inputs we consider in our model is the unitary capture cost of aluminium smelters, which is set at 211.2 €/tCO_2. This cost is significantly higher than the costs of other sectors, making aluminium smelters less favorable for integration into the CCS network. However, as previously mentioned, Norsk Hydro is proactively investing in CO_2 capture technologies for existing smelters, with the aim of making them more economically feasible and widely applicable. Therefore, we have carried out a sensitivity analysis on the unitary capture cost of aluminium smelters ($UCC_{a,smelt}$) to determine the threshold cost that aluminium smelters must achieve to have an impact on the CCS network in Norway.

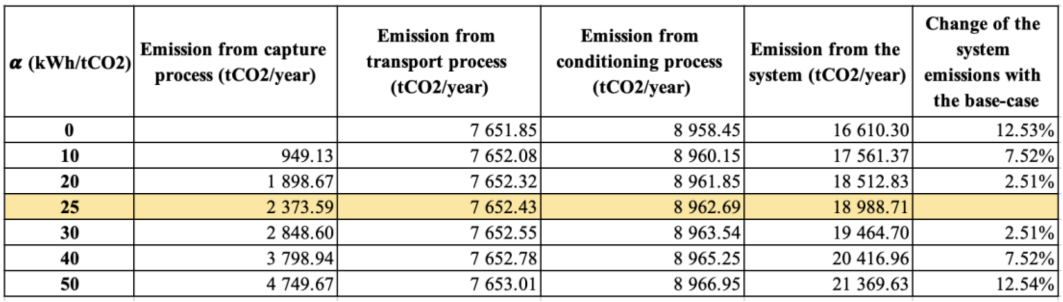
To perform the sensitivity analysis, we changed the unitary capture cost of aluminium smelters from 211.2 €/tCO_2 to 190, 160, 130, 100, 90, 80, 75 and 70 €/tCO_2 and ran the model for each value. The results indicate that only when the cost is reduced to 70 €/tCO_2 is there a change occurring in the network. Specifically, this reduction prompts the installation of capture units in smelters at Hydro Aluminum Karmøy and Sør-Norge Aluminium, while decreasing the captured amount from Heidelberg materials Brevik.

Although the unitary capture cost of 70 €/tCO_2 remains the highest among all sectors, the proximity of Hydro Aluminum Karmøy and Sør-Norge Aluminium to the storage sites makes them valuable additions to the network. Especially, Sør-Norge Aluminium, together with Mongstad refinery, serve as strategic points for collecting emissions before transferring them to the storage sites. By utilizing smelters at these two plants and reducing and captured amount at a more distant plant, the network can lower the transport cost and emissions, compensating for the increase in the capture cost.

Indeed, the economic results indicate that adjusting $UCC_{a,smelt}$ to 70 €/tCO_2 results in an increase in the capture cost from 227 to 230 M€/year, but a decrease in the transport cost from 49 to 44 M€/year, leading to an overall saving of 2 M€/year. Additionally, the emissions of the system also show a decline from 18.99 kt/year to 18.65 kt/year. In a nutshell, the cost-optimal supply chain network in scenario 6 is only slightly sensitive to the unitary capture cost of aluminium smelters.

5.3.3. Electricity consumed for the capture process

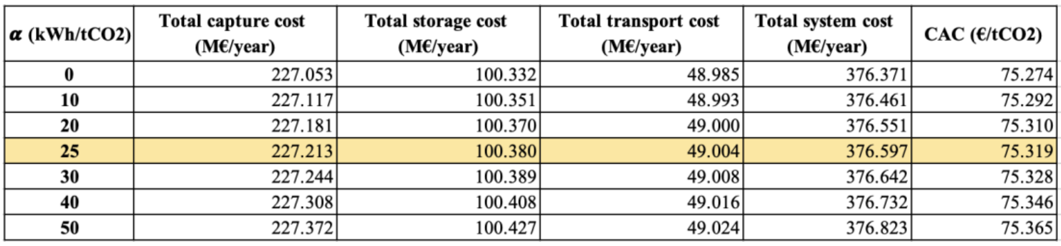
In our model, the emissions from the capture process depends remarkably on electricity required to capture one metric tonne of CO_2 (α). Therefore, we adjusted the value of electricity consumed to capture one tonne of CO_2 for all sectors except for cement production, which is already set to be zero based on the current situation in Norway, to investigate if such a change exerts an effect on the network design.



α (kWh/tCO2)	**Emission from capture process (tCO2/year)**	**Emission from transport process (tCO2/year)**	**Emission from conditioning process (tCO2/year)**	**Emission from the system (tCO2/year)**	**Change of the system emissions with the base-case**
0		7 651.85	8 958.45	16 610.30	12.53%
10	949.13	7 652.08	8 960.15	17 561.37	7.52%
20	1 898.67	7 652.32	8 961.85	18 512.83	2.51%
25	2 373.59	7 652.43	8 962.69	18 988.71	
30	2 848.60	7 652.55	8 963.54	19 464.70	2.51%
40	3 798.94	7 652.78	8 965.25	20 416.96	7.52%
50	4 749.67	7 653.01	8 966.95	21 369.63	12.54%

Table 5.5. Emisions from different processes for different values of electricity consumed for capture process

The result reveals that when the amount of electricity consumed to capture one tonne of CO_2 rises, the emissions from capture process increases, meaning that when α is lower than 25 (the value in the base-case), the emissions from the capture process are lower than those in the base-case and vice versa. This, in turn, leads to a moderate growth in the total emissions of the system for the increase of α, as indicated in Table 5.5. To compensate for this change in emissions and comply with the carbon reduction target, the system needs to adjust the amount of CO_2 captured. As a result, the related costs of the system exhibit minor differences across the different values of α (Table 5.6).



α (kWh/tCO2)	**Total capture cost (M€/year)**	**Total storage cost (M€/year)**	**Total transport cost (M€/year)**	**Total system cost (M€/year)**	**CAC (€/tCO2)**
0	227.053	100.332	48.985	376.371	75.274
10	227.117	100.351	48.993	376.461	75.292
20	227.181	100.370	49.000	376.551	75.310
25	227.213	100.380	49.004	376.597	75.319
30	227.244	100.389	49.008	376.642	75.328
40	227.308	100.408	49.016	376.732	75.346
50	227.372	100.427	49.024	376.823	75.365

Table 5.6. Economic indicators for different values of electricity consumed for capture process

However, it is worth emphasizing that these changes in costs are primarily driven by the fluctuations in the amount of CO_2 captured, rather than differences in the network configuration. In fact, the resulting optimal designs of CCS supply chain remain essentially identical regardless the value of α, meaning that the networks use the same sources, transport connections and transport technology as in the base-case. Therefore, it can be concluded that the supply chain design is not sensitive to the electricity required for capturing one tCO_2.

5.3.4. Unitary transport cost for truck

In our model, the truck transport only plays a minor role in comparison with other transport technologies. This is partly due to the high cost of transporting CO_2 via truck. Therefore, it is here examined the impact of lowering unitary truck transport cost on the design optimization of CCS supply chain.

The results present two distinct patterns based on the unitary truck transport cost: one where the unit cost is equal or greater than 0.135 €/tCO_2 (Group A), and another where the cost is less than 0.135 €/tCO_2 (Group B). In Group A, the transportation network remains unchanged compared to the base case. However, in Group B, there is a substitution of truck transport for one pipeline route connecting Elkem Thamshavn and Wacker Chemical Norway. This route transfers approximately 130 kt CO_2 over a distance of 51.1 km. Nevertheless, pipeline transport continues to be the primary mode of connection in both groups.

Unitary transport cost of truck (€/tCO2)	Total capture cost (M€/year)	Total storage cost (M€/year)	Total transport cost (M€/year)	Total system cost (M€/year)	CAC (€/tCO2)
0.105	227.264	100.395	48.756	376.416	75.283
0.120	227.264	100.395	48.854	376.514	75.303
0.135	227.213	100.380	49.004	376.597	75.319
0.150	227.213	100.380	49.004	376.597	75.319
0.165	227.213	100.380	49.004	376.597	75.319
0.195	227.213	100.380	49.004	376.597	75.319
0.225	227.213	100.380	49.004	376.597	75.319
0.240	227.213	100.380	49.004	376.597	75.319

Table 5.7. The result of the sensitivity analysis on unitary transport cost of truck regarding cost indicators of the system

Concerning cost and emissions indicators of the system, in Group A, all indicators stay the same as in the base case (Table 5.7 and Figure 5.19). However, slight differences can be witnessed in Group B. The total capture and storage costs in Group B are constant across different values of unitary truck transport cost and are slightly higher than those in the base case, +0.051 M€/year and +0.015 M€/year, respectively (Table 5.7). On the other hand, the total transport cost increases as the unitary transport cost of truck rises, but the cost is still lower than that of the base case. Moreover, the change in the total transport cost is more significant than the changes in the total capture and storage costs, causing the total system cost and CAC to vary following the same pattern as the total transport cost.

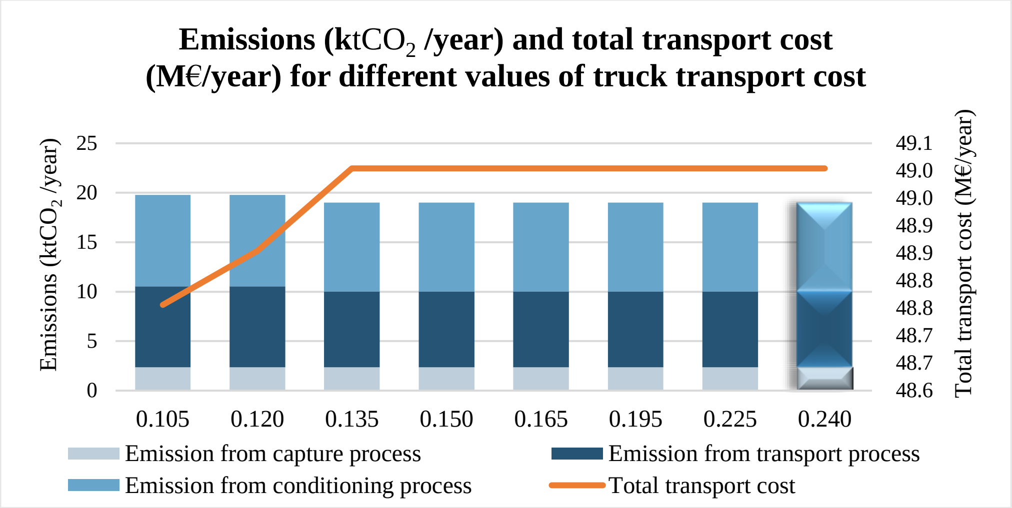


Figure 5.19. Results of emissions and total transport cost for different values of unitary truck transport cost

The emissions of the systems in Group B also remain unchanged regardless of the value of the unit transport cost of truck, but they are higher compared to the base case (as demonstrated in Figure 5.19). This increase in emissions can be attributed to two factors related to the transport and conditioning processes. Firstly, the higher emissions from transport process are a result of the truck transport emitting more emissions than the pipeline transport. Therefore, when the truck transport is used in Group B instead of pipeline, the overall emissions from transportation increase. Secondly, the increase in the emissions from conditioning process is due to two reasons: (1) more energy is required to adjust condition of CO_2 from its capture state to condition suitable for truck transport; (2) extra energy is needed in the systems of Group B to move CO_2 from the truck transport to the pipeline transport.

In summary, though very low unitary transport costs of truck can extend the application of truck in the CCS supply chain network, the transport configurations still mainly rely on pipeline technology. Moreover, it is crucial to recognize that achieving such low unit truck transport cost, especially for short distance and low capacities, is still challenging. Therefore, it can be concluded that the model is slightly sensitive to the unitary transport cost of truck.

6. Conclusion

In this chapter, we will elaborate on our answer to the research question, theoretical and practical implications, limitations of this paper and suggestions for future research.

6.1. Answering research question

The goal of this thesis is to investigate "How can the supply chain network for CO_2 capture, transportation and storage be designed to minimize total costs and meet the CO_2 avoidance targets?". This research question was answered by: (1) developing a mathematical model to optimize the system cost and total avoided CO_2 for CCS supply chain; (2) analyzing the systems across different CO_2 abatement targets to provide insights into how to design such a network.

Regarding the model, a static, multi-stage, multi-echelon and multi-objective MILP model was built to optimize the design of CCS supply chain. Additionally, the Gurobi 10.0.1 software package was utilized to solve the model. The model has two different objectives: minimizing the total system cost and maximizing the amount of CO_2 avoided. The ε-constraint approach was chosen for this paper as it allows the illustration of trade-offs between these conflicting objectives through a Pareto curve. Specifically, the objective of the model was set to minimize the total system cost, while simultaneously constraining the total amount of CO_2 avoided to specific values based on different carbon reduction targets. Nine prototypical Pareto-optimal supply chain configurations were detailed to describe the changes in system design with the evolution of emissions reduction targets.

The findings indicate that as the target of avoided CO_2 increases, ranging from 5% to its maximum attainable value equivalent to 83% of the total current emissions from studied plants, the minimum cost for the network also rises progressively from 21.4 to 938.7 M€/year. On average, the capture cost constitutes the largest share of the total cost at 52%, while the storage and transport costs account for 30% and 17% respectively. Furthermore, it is found that avoiding a fixed amount of CO_2 becomes more expensive as the target for reducing emissions becomes more demanding. Specifically, the total cost of avoided carbon starts from 42.9 €/tCO_2 in scenario 1, increases throughout scenarios 2 and 8, and reaches 117.6 €/tCO_2 in scenario 9. This increase is primarily driven by the higher specific capture cost across different scenarios.

Concerning the emissions embodied in the system, in all scenarios, they remain below 1% of the total volume of stored CO_2. When analyzing the contributors to the system emissions, it was observed that the emissions from capture process cover the smallest proportion of the overall emissions (less than 20%). Meanwhile, the rankings of the emissions from transport and conditioning processes could be influenced by factors such as travelling long distances or utilizing ship transport.

While the decisions regarding storage sites are irrelevant in this study, the selection of capture sites plays a key role in optimizing the network design. As the carbon avoidance target increases, the optimal network becomes more complex with more capture units being deployed. Starting from scenario 7, where the aim is to avoid 6 Mt/year, equivalent to 62% of the total current emissions from studied sources, capture units situated far away from the northern region start to be installed to meet the emissions targets. This leads to the transportation of CO_2 over longer distances. In scenarios 8 and 9, where the targets are the highest, capture units are even installed at aluminium smelters that are characterized by the highest unitary capture cost, leading to an upsurge in the overall capture cost.

Regarding prioritizing the installation of capture units at various CO_2 sources, the solver takes into account four criteria: unitary capture cost, location, size of CO_2 emissions, and capture efficiency. As a result, for small emissions targets, four plants in the natural gas processing/fertilizer and refinery/petrochemical sectors are utilized first. The installation of capture units at aluminium smelters is considered a last resort given their extremely high cost. Furthermore, as the mitigation target becomes more ambitious, the optimal supply chain networks evolve and give rise to different clusters of sources in the Southern, Southwestern and Western, Central and Western, and finally Northern regions, allowing for the utilization of shared infrastructure and providing opportunities to capture from small sources.

In terms of the transport process, the complexity of the transport system in the CCS supply chain increases with the higher emissions targets. Across nine scenarios examined, pipeline technology is predominantly employed for transferring the captured CO_2, but only for distances less than 420 km. On the other hand, truck transport and ship transport play a minor role in the transport networks. Trucks are selected for relatively small CO_2 flow rates (under 60 kt) and short distances, while ship transport is only utilized when higher emissions targets necessitate capturing CO_2 from sources located in the northern region of Norway. In such scenarios, ship routes cover distances exceeding 980 km. It is important to note that although ships may be preferred to transport CO_2 captured from distant regions, long-distance travelling can amplify emissions related to ship transport technology installation.

6.2. Theoretical implications

Although there exists certain research on SCND for CCS, most of them focused on problems at region-wide or continent-wide levels and with a single economic objective. Moreover, these studies generally consider emission sources from limited sectors and examine only pipeline and/or ship as the potential transport modes for the CCS network. In our study, a multi-objective MILP model was formulated to allow for finding minimum-cost networks under different CO_2 avoidance targets. Meanwhile, we provide a comprehensive model that incorporates three modes of transport, namely pipeline, truck and ship, and takes into account emissions sources from various sectors. The model exhibits flexibility and generalization, allowing its application to various contexts beyond the specific study.

The findings of the study highlight the significant contribution of the capture cost to the total cost, which is in line with the existing literature. The selection of CO_2 sources and the sizing of capture plants play a pivotal role in designing an optimal CCS supply chain network. Besides the cost aspect, we found through the sensitivity analysis that changing capture efficiency also makes a significant impact on the network. A higher capture efficiency implies lower capture and transport costs as well as lower emissions of the system and vice versa.

By conducting research at a country level, we can also assess the possibility of clustering small emissions sources within the CCS network. Our findings suggest that clustering is more feasible when the sources are geographically close to each other. The proximity reduces the transportation distances and associated costs for CO2 transport. Besides, the combined emissions from the small sources should be significant enough to justify the cost and effort of implementing shared transport infrastructure. If the emissions from individual sources are too small, it may not be economically viable to cluster them.

Furthermore, our findings regarding the transport process agree with the existing literature. Particularly, the results pinpoint that pipeline transport represents as the most cost-effective method for transporting the captured CO_2, but only for short to medium distances. For longer distances, ship transport is proven to be a more attractive option than pipeline. Finally, truck technology has the potential to transport CO_2 for short distances and low flow rates.

6.3. Practical implications

Due to the lack of prior study on the CCS supply chain network design in Norway, our study holds important implications for the Norwegian industry and decision-makers in developing and implementing a cost-minimal network for the evolution of emissions reduction targets. The optimization results point out the optimal selection, location, and sizing of capture units across different sectors and the most suitable transportation routes and modes among ship, truck, and pipeline for practitioners to refer to.

Evaluating the carbon-avoided cost provides Norwegian leaders with insights into the policy of carbon tax in Norway to facilitate the implementation of CCS networks. It is recommended that a carbon tax should range from 75.3 to 94.4 €/tCO2 for avoiding 52% to 72% of total current emissions from considered sources. In the case of maximizing CO2 avoidance, which corresponds to 83% of the total current emissions, the carbon tax should be set at least at 117.6 €/tCO2 to compensate for the investment and operation of the system.

In terms of the capture stage, besides efforts to reduce capture costs, the findings suggest that the Norwegian industry should also focus on improving capture efficiency. For scenario 6 with the aim to avoid 5 MtCO2/year which we believe is aligned with the current target in Norway, increasing capture efficiency to 90% for all sources helps to reduce the transport cost significantly by 18.4%. Additionally, for the aluminium industry, they should develop technologies that can lower the cost of capturing CO2 from smelters to 70 €/tCO2. Failure to achieve this cost reduction would make aluminium smelters remain unfavorable for an economically viable supply chain network in scenario 6. Finally, it is recommended to develop the CCS network in clusters rather than relying solely on standalone large-scale sources to better utilize resources and benefit from the economies of scale. The initial focus should be on Southern, Southwestern and Western areas.

When it comes to the transport stage, our study highlights that pipeline transport is the most favorable and cost-effective option for transferring CO_2. As a result, to establish an efficient CCS network in Norway, it is recommended to prioritize investment and development in pipeline infrastructure, while ship transport can be employed at a later stage when emissions targets become more ambitious. From the sensitivity analysis, it is also suggested that with the current Norwegian target, truck transport cost holds the potential only when its unitary cost is deeply reduced to below 0.135 €/tCO2/km for the distance range below 75km.

6.4. Limitation and suggestion

6.4.1. Limitation

The most notable limitation of this research lies in the willingness of practitioners to take part in interviews or reply to emails. This difficulty was faced in the attempts to get answers from scientists or researchers on each process of CCS in Norway, including capture, transport, and storage processes. Following this limitation, we were only able to get responses from one person for each aspect of CCS system. This prevents us from acquiring sufficient quantitative data to come up with a more complete picture of CCS supply chain network in Norway.

Additionally, due to the time constraint of a master thesis, the investigation of the impact of time-dependent factors on the CCS system is still missing in this study. In other words, the focus of this research is on the steady state optimal CCS network design rather than its optimal evolution over time. Moreover, although uncertainties, such as uncertainties of storage capacity, polices or investment cost, have been recognized as influential factors in the development of CCS network (Koelbl et al., 2014), it is neglected in this study. Besides, owing to the lack of available data, the scale effects of the plant size on the capture costs and the distinction between onshore pipeline and offshore pipeline are not addressed in this study, even though it could impact the design of CCS network. Despite these limitations, we believe that this paper still provides interesting findings and applicable tools and methods for decision-makers and researchers.

6.4.2. Suggestion

Based on our limitations, there are some suggestions for future research. Firstly, to improve the model, future research can investigate the impacts of time-dependent factors, uncertainties or differentiating between onshore and offshore pipelines on the development of CCS network to gain a more robust analysis of the optimal SCND for CCS.

For the capture stage, future research should explore scale effects on unitary capture costs because of plant size to better assess the feasibility of clustering small sources.

Researchers could also investigate the possibility of different sources sharing not only transport but also capture facilities to utilize the scale effects and allocate resources better. In sectors whose CO2 emissions arise from multiple process units such as iron and steel, refinery and petrochemical, it is advisable to establish differentiated costs that accurately reflect the diverse nature of the capture process. When it comes to the storage stage, once more information about the costs and locations of receiving terminals and storage sites of LUNA and Smeaheia is provided, it should be updated to the model to yield relevant findings about source-sink matching.

References

Ağralı, S., Üçtuğ, F. G., & Türkmen, B. A. (2018). An optimization model for carbon capture & storage/utilization vs. carbon trading: A case study of fossil-fired power plants in Turkey. *Journal of Environmental Management*, *215*, 305–315. https://doi.org/10.1016/j.jenvman.2018.03.054

Aker Carbon Capture. (n.d.). *Key projects*. Aker Carbon Capture. Retrieved June 4, 2023, from https://akercarboncapture.com/about-us/key-projects/

Akerboom, S., Waldmann, S., Mukherjee, A., Agaton, C., Sanders, M., & Kramer, G. J. (2021). Different This Time? The Prospects of CCS in the Netherlands in the 2020s. *Frontiers in Energy Research*, *9*. https://www.frontiersin.org/articles/10.3389/fenrg.2021.644796

Al Baroudi, H., Awoyomi, A., Patchigolla, K., Jonnalagadda, K., & Anthony, E. J. (2021). A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage. *Applied Energy*, *287*, 116510. https://doi.org/10.1016/j.apenergy.2021.116510

Ali, H. (2019). *Techno-economic analysis of CO2 capture concepts* [Doctoral thesis, University of South-Eastern Norway]. https://openarchive.usn.no/usn-xmlui/handle/11250/2622802

Amir Mohammad, F. F., Gholian-Jouybari, F., Mohammad, M. P., & Mostafa, H.-K. (2017). A Bi-Objective Stochastic Closed-loop Supply Chain Network Design Problem Considering Downside Risk. *Industrial Engineering & Management Systems*, *16*(3), 342–362. https://doi.org/10.7232/iems.2017.16.3.342

Ansaloni, L., Alcock, B., & Peters, T. A. (2020). Effects of CO2 on polymeric materials in the CO2 transport chain: A review. *International Journal of Greenhouse Gas Control*, *94*, 102930. https://doi.org/10.1016/j.ijggc.2019.102930

Anuradha Varanasi. (2019, September 27). *Does Carbon Capture Technology Actually Work?* State of the Planet. https://news.climate.columbia.edu/2019/09/27/carbon-capture-technology/

Ashworth, P., Wade, S., Reiner, D., & Liang, X. (2015). Developments in public communications on CCS. *International Journal of Greenhouse Gas Control*, *40*, 449–458. https://doi.org/10.1016/j.ijggc.2015.06.002

Aspelund, A., & Jordal, K. (2007). Gas conditioning—The interface between CO2 capture and transport. *International Journal of Greenhouse Gas Control*, *1*(3), 343–354. https://doi.org/10.1016/S1750-5836(07)00040-0

Aspelund, A., Mølnvik, M. J., & De Koeijer, G. (2006). Ship Transport of CO2: Technical Solutions and Analysis of Costs, Energy Utilization, Exergy Efficiency and CO2 Emissions. *Chemical Engineering Research and Design*, *84*(9), 847–855. https://doi.org/10.1205/cherd.5147

Aspelund, A., Sandvik, T. E., Krogstad, H., & De Koeijer, G. (2005). - Liquefaction of captured CO2 for ship-based transport. In E. S. Rubin, D. W. Keith, C. F. Gilboy, M. Wilson, T. Morris, J. Gale, & K. Thambimuthu (Eds.), *Greenhouse Gas Control Technologies 7* (pp. 2545–2549). Elsevier Science Ltd. https://doi.org/10.1016/B978-008044704-9/50370-0

Babazadeh, R., Razmi, J., Pishvaee, M. S., & Rabbani, M. (2017). A sustainable second-generation biodiesel supply chain network design problem under risk. *Omega*, *66*, 258–277. https://doi.org/10.1016/j.omega.2015.12.010

Bäckstrand, K., Meadowcroft, J., & Oppenheimer, M. (2011). The politics and policy of carbon capture and storage: Framing an emergent technology. *Global Environmental Change-Human and Policy Dimensions - GLOBAL ENVIRON CHANGE*, *21*, 275–281. https://doi.org/10.1016/j.gloenvcha.2011.03.008

Bains, P., Psarras, P., & Wilcox, J. (2017). CO2 capture from the industry sector. *Progress in Energy and Combustion Science*, *63*, 146–172. https://doi.org/10.1016/j.pecs.2017.07.001

Barker, D. J., Turner, S. A., Napier-Moore, P. A., Clark, M., & Davison, J. E. (2009). CO2 Capture in the Cement Industry. *Energy Procedia*, *1*(1), 87–94. https://doi.org/10.1016/j.egypro.2009.01.014

Basile, A., Gugliuzza, A., Iulianelli, A., & Morrone, P. (2011). 5—Membrane technology for carbon dioxide (CO2) capture in power plants. In A. Basile & S. P. Nunes (Eds.), *Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications* (pp. 113–159). Woodhead Publishing. https://doi.org/10.1533/9780857093790.2.113

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., & Mazzotti, M. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control*, *117*, 103635. https://doi.org/10.1016/j.ijggc.2022.103635

Berghout, N., van den Broek, M., & Faaij, A. (2013). Techno-economic performance and challenges of applying CO2 capture in the industry: A case study of five industrial plants. *International Journal of Greenhouse Gas Control*, *17*, 259–279. https://doi.org/10.1016/j.ijggc.2013.04.022

Bilsbak, V. (2009). Conditioning of CO2 coming from a CO2 capture process for transport and storage purposes [Master thesis, Institutt for energi- og prosessteknikk]. In *92*. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/233677

Bjerketvedt, V. S., Tomasgard, A., & Roussanaly, S. (2020). Optimal design and cost of ship-based CO2 transport under uncertainties and fluctuations. *International Journal of Greenhouse Gas Control*, *103*, 103190. https://doi.org/10.1016/j.ijggc.2020.103190

Boot-Handford, M., Abanades, J., Anthony, E., Blunt, M., Brandani, S., Mac Dowell, N., Andez, J., Ferrari, M.-C., Gross, R., Hallett, J., Haszeldine, R. S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R., Pourkashanian, M., Rochelle, G., Shah, N., & Fennell, P. (2014). Carbon capture and storage update. *Energy & Environmental Science*, *7*, 130–189. https://doi.org/10.1039/c3ee42350f

Borg CO2. (n.d.). *Borg CO2*. Borg CO2. Retrieved May 31, 2023, from https://www.borgco2.no

Brevik CCS. (n.d.). *Brevik CCS – World's first CO2-capture facility at a cement plant*. Brevik CSS. Retrieved June 4, 2023, from https://www.brevikccs.com/en/welcome-to-brevik-ccs

Brownsort, P. (2015). *Ship transport of CO$_2$ for Enhanced Oil Recovery—Literature Survey* [Technical Report]. Scottish Carbon Capture and Storage (SCCS). https://era.ed.ac.uk/handle/1842/15727

Brownsort, P., Carruthers, K., Consulting, D., Energy, E., Haszeldine, R., Johnson, G., Kapila, R. V., Kemp, A., Littlecott, C., Mabon, L., Mackay, E., Macrory, R., Meyvis, B., Olden, P. H., Paisley, R., Paterson, J., Pickup, G., Piessens, K., Stewart, J., … Welkenhuysen, K. (2015, June 1). *CO$_2$ storage and Enhanced Oil Recovery in the North Sea: Securing a low-carbon future for the UK*. https://www.semanticscholar.org/paper/CO%E2%82%82-storage-and-Enhanced-Oil-Recovery-in-the-North-Brownsort-Carruthers/c0900659912fc310099dc3252662286c7f3f50d4

Bryman, A., Bell, E., & Harley, B. (2019). *Business research methods* (Fifth edition). Oxford University Press.

Budinis, S., Krevor, S., Dowell, N., Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews*, *22*, 61–81. https://doi.org/10.1016/j.esr.2018.08.003

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., … Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science*, *11*(5), 1062–1176. https://doi.org/10.1039/C7EE02342A

Carpenter, S. M., & Long, H. A. (2017). 13—Integration of carbon capture in IGCC systems. In T. Wang & G. Stiegel (Eds.), *Integrated Gasification Combined Cycle (IGCC) Technologies* (pp. 445–463). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100167-7.00036-6

CCS Norway. (n.d.-a). *Ambitious goals | A contribution in the development of CCS*. Retrieved May 18, 2023, from https://ccsnorway.com/ambitious-goals/

CCS Norway. (n.d.-b). *The Longship CCS project in Norway | Learn more about the project*. Retrieved May 31, 2023, from https://ccsnorway.com/the-project/

Center for Climate and Energy Solutions. (n.d.). Global Emissions. *Center for Climate and Energy Solutions*. Retrieved May 14, 2023, from https://www.c2es.org/content/international-emissions/

Chemical Engineering. (2020). *The Chemical Engineering Plant Cost Index—Chemical Engineering*. https://www.chemengonline.com/pci-home

Chen, W., van der Ham, L., Nijmeijer, A., & Winnubst, L. (2015). Membrane-integrated oxy-fuel combustion of coal: Process design and simulation. *Journal of Membrane Science, 492,* 461–470. https://doi.org/10.1016/j.memsci.2015.05.062

Chopra, S., & Meindl, P. (2016). *Supply Chain Management: Strategy, Planning, and Operation* (sixth edition).

CICERO. (2019). *The role of Carbon Capture and Storage in the Mitigation of Climate Change*. https://pub.cicero.oslo.no/cicero-xmlui/bitstream/handle/11250/2633470/CICERO%20Report%202019%2021%20web.pdf?sequence=1&isAllowed=y

CO2datashare. (n.d.). *Smeaheia Dataset—CO2DataShare*. Retrieved May 31, 2023, from https://co2datashare.org/dataset/smeaheia-dataset#org1575472

Collodi, G. (2010). Hydrogen Production via Steam Reforming with CO2 Capture. *Chemical Engineering Transactions*, *19*, 37–42. https://doi.org/10.3303/CET1019007

d'Amore, F., & Bezzo, F. (2017). Economic optimisation of European supply chains for CO 2 capture, transport and sequestration. *International Journal of Greenhouse Gas Control*, *65*, 99–116. https://doi.org/10.1016/j.ijggc.2017.08.015

d'Amore, F., Mocellin, P., Vianello, C., Maschio, G., & Bezzo, F. (2018). Economic optimisation of European supply chains for CO 2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures. *Applied Energy*, *223*, 401–415. https://doi.org/10.1016/j.apenergy.2018.04.043

d'Amore, F., Romano, M. C., & Bezzo, F. (2021a). Carbon capture and storage from energy and industrial emission sources: A Europe-wide supply chain optimisation. *Journal of Cleaner Production*, *290*, 125202. https://doi.org/10.1016/j.jclepro.2020.125202

d'Amore, F., Romano, M. C., & Bezzo, F. (2021b). Optimal design of European supply chains for carbon capture and storage from industrial emission sources including pipe and ship transport. *International Journal of Greenhouse Gas Control*, *109*, 103372. https://doi.org/10.1016/j.ijggc.2021.103372

d'Amore, F., Sunny, N., Iruretagoyena, D., Bezzo, F., & Shah, N. (2019a). European supply chains for carbon capture, transport and sequestration, with uncertainties in geological storage capacity: Insights from economic optimisation. *Computers & Chemical Engineering*, *129*, 106521. https://doi.org/10.1016/j.compchemeng.2019.106521

d'Amore, F., Sunny, N., Iruretagoyena, D., Bezzo, F., & Shah, N. (2019b). Optimising European supply chains for carbon capture, transport and sequestration, including uncertainty on geological storage availability. In A. A. Kiss, E. Zondervan, R. Lakerveld, & L. Özkan (Eds.), *Computer Aided Chemical Engineering* (Vol. 46, pp. 199–204). Elsevier. https://doi.org/10.1016/B978-0-12-818634-3.50034-5

Dasari, G., Usadi, A. K., Jones, S. A., Senkel, J. W., Li, Y. E., Wissam, A. K. S., Togabekov, A., Tan, X. W., Loh, W. L., Wang, X., & Jiao, J. (2022). *South*

East Asia CO2 Source Sink Mapping to Optimize Transport Cost Using Pipelines and Ships (SSRN Scholarly Paper No. 4285767). https://doi.org/10.2139/ssrn.4285767

Deacon, D., Bryman, A., & Fenton, N. (1998). Collision or collusion? A discussion and case study of the unplanned triangulation of quantitative and qualitative research methods. *International Journal of Social Research Methodology*, *1*(1), 47–63. https://doi.org/10.1080/13645579.1998.10846862

Decarre, S., Berthiaud, J., Butin, N., & Guillaume-Combecave, J.-L. (2010). CO2 maritime transportation. *International Journal of Greenhouse Gas Control*, *4*(5), 857–864. https://doi.org/10.1016/j.ijggc.2010.05.005

Devika, K., Jafarian, A., & Nourbakhsh, V. (2014). Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. *European Journal of Operational Research*, *235*(3), 594–615. https://doi.org/10.1016/j.ejor.2013.12.032

Duan, L., & Li, L. (2023). *OCAC Technology in Oxy-Fuel Combustion for Carbon Capture* (pp. 65–77). https://doi.org/10.1007/978-981-19-9127-1_4

Dubois, A., & Gadde, L.-E. (2002). Systematic combining: An abductive approach to case research. *Journal of Business Research*, *55*(7), 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8

Dul, J., & Hak, T. (2007). *Case Study Methodology in Business Research*. Routledge.

Dzupire, N. C., & Nkansah-Gyekye, Y. (2014). *A Multi-Stage Supply Chain Network Optimization Using Genetic Algorithms* (arXiv:1408.0614). arXiv. https://doi.org/10.48550/arXiv.1408.0614

EEA. (2017). *Renewables successfully driving down carbon emissions in Europe—European Environment Agency* [News]. https://www.eea.europa.eu/highlights/renewables-successfully-driving-down-carbon

Elahi, N., Shah, N., Korre, A., & Durucan, S. (2014). Multi-period Least Cost Optimisation Model of an Integrated Carbon Dioxide Capture Transportation and Storage Infrastructure in the UK. *Energy Procedia*, *63*, 2655–2662. https://doi.org/10.1016/j.egypro.2014.11.288

Elahi, N., Shah, N., Korre, A., & Durucan, S. (2017). Multi-stage Stochastic Optimisation of a CO2 Transport and Geological Storage in the UK. *Energy*

Procedia, *114*, 6514–6525. https://doi.org/10.1016/j.egypro.2017.03.1787

Elhenawy, S., Khraisheh, M., Almomani, F., & Walker, G. (2020). Metal-Organic Frameworks as a Platform for CO2 Capture and Chemical Processes: Adsorption, Membrane Separation, Catalytic-Conversion, and Electrochemical Reduction of CO2. *Catalysts*, *10*, 1293. https://doi.org/10.3390/catal10111293

Engel, F., & Kather, A. (2017). Conditioning of a Pipeline CO2 Stream for Ship Transport from Various CO2 Sources. *Energy Procedia*, *114*, 6741–6751. https://doi.org/10.1016/j.egypro.2017.03.1806

Equinor. (n.d.-a). *Carbon capture, utilisation and storage (CCS)*. Retrieved May 18, 2023, from https://www.equinor.com/energy/carbon-capture-utilisation-and-storage

Equinor. (n.d.-b). *Sleipner area*. Retrieved May 31, 2023, from https://www.equinor.com/energy/sleipner

Equinor. (2008, April 23). *Carbon storage started on Snøhvit—Equinor.com*. https://www.equinor.com/news/archive/2008/04/23/CarbonStorageStartedOnSnhvit

Equinor. (2022a, March 31). *CCS on Sleipner – back where it came from*. Equinor. https://equinor.industriminne.no/en/ccs-on-sleipner-back-where-it-came-from/

Equinor. (2022b, April 5). *Equinor awarded the Smeaheia and Polaris CO2 licenses—Equinor.com*. https://www.equinor.com/news/archive/20220405-awarded-smeaheia-polaris-co2-licenses

Erkut, E., Karagiannidis, A., Perkoulidis, G., & Tjandra, S. A. (2008). A multicriteria facility location model for municipal solid waste management in North Greece. *European Journal of Operational Research*, *187*(3), 1402–1421. https://doi.org/10.1016/j.ejor.2006.09.021

European Commission. (n.d.-a). *Consequences of climate change*. Retrieved May 14, 2023, from https://climate.ec.europa.eu/climate-change/consequences-climate-change_en

European Commission. (n.d.-b). *EU Emissions Trading System (EU ETS)*. Retrieved May 17, 2023, from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2020). *Carbon capture, use and storage*.

https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage_en

Exchange Rates. (n.d.). *Euro to US Dollar Spot Exchange Rates for 2020*. Retrieved June 19, 2023, from https://www.exchangerates.org.uk/EUR-USD-spot-exchange-rates-history-2020.html?fbclid=IwAR1S-S7n4OgDkTIfwUj_5XTdthgDTdykAgyhHuuIpKRgW0cmEyRErYbuiaM

Farahani, R. Z., Rezapour, S., Drezner, T., & Fallah, S. (2014). Competitive supply chain network design: An overview of classifications, models, solution techniques and applications. *Omega*, *45*, 92–118. https://doi.org/10.1016/j.omega.2013.08.006

Federico d'Amore, Lovisotto, L., & Bezzo, F. (2020). Introducing social acceptance into the design of CCS supply chains: A case study at a European level. *Journal of Cleaner Production*, *249*, 119337. https://doi.org/10.1016/j.jclepro.2019.119337

Filippov, S. P., & Zhdaneev, O. V. (2022). Opportunities for the Application of Carbon Dioxide Capture and Storage Technologies in Case of Global Economy Decarbonization (Review). *Thermal Engineering*, *69*(9), 637–652. https://doi.org/10.1134/S0040601522090014

Forbes, S. M., Verma, P., Curry, T. E., Friedmann, S. J., & Wade, S. M. (2008). Guidelines for carbon dioxide capture, transport and storage. *Guidelines for Carbon Dioxide Capture, Transport and Storage*. https://www.cabdirect.org/cabdirect/abstract/20113082154

Fragoso, R., Bushenkov, V., & Ramos, M. J. (2021). Multi-criteria supply chain network design using interactive decision maps. *Journal of Multi-Criteria Decision Analysis*, *28*(5–6), 220–233. https://doi.org/10.1002/mcda.1744

Gao, L., Fang, M., Li, H., & Hetland, J. (2011). Cost analysis of CO2 transportation: Case study in China. *Energy Procedia*, *4*, 5974–5981. https://doi.org/10.1016/j.egypro.2011.02.600

Gardarsdottir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., Pérez-Calvo, J.-F., Berstad, D., Fu, C., Anantharaman, R., Sutter, D., Gazzani, M., Mazzotti, M., & Cinti, G. (2019). Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis. *Energies*, *12*(3), 542. https://doi.org/10.3390/en12030542

GASSNOVA. (n.d.). *Gassnova—The Norwegian state enterprise for CCS*. Retrieved May 22, 2023, from https://gassnova.no/en/gassnova-en

Gassnova. (2020). *REGULATORY LESSONS LEARNED FROM LONGSHIP*.

Georgiadis, M. C., Tsiakis, P., Longinidis, P., & Sofioglou, M. K. (2011). Optimal design of supply chain networks under uncertain transient demand variations. *Omega*, *39*(3), 254–272. https://doi.org/10.1016/j.omega.2010.07.002

Global CCS Institute. (n.d.). *About*. Global CCS Institute. Retrieved May 22, 2023, from https://www.globalccsinstitute.com/about/

Global CCS Institute. (2017). *The Global Status of CCS: 2017*. https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf

Global CCS Institute. (2019). *Global Status of CCS:2019*. https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

Global CCS Institute. (2020a). *SCALING UP THE CCS MARKET TO DELIVER NET-ZERO EMISSIONS*.

Global CCS Institute. (2022). *GLOBAL STATUS OF CCS 2022*. https://status22.globalccsinstitute.com/wp-content/uploads/2023/03/GCCSI_Global-Report-2022_PDF_FINAL-01-03-23.pdf

Global CCS Institute. (2020b, July). *Carbon capture and storage: Challenges, enablers and opportunities for deployment*. Global CCS Institute. https://www.globalccsinstitute.com/news-media/insights/carbon-capture-and-storage-challenges-enablers-and-opportunities-for-deployment/

Global CCS Institute. (2021, March 29). *Technology Readiness and Costs of CCS - Global CCS Institute*. https://www.globalccsinstitute.com/resources/publications-reports-research/technology-readiness-and-costs-of-ccs/

Global CCS Institute. (2023, March 15). *CCS Commercial and Regulatory Frameworks: Lessons Learned from CCS Front-runners in Norway*. Global CCS Institute. https://www.globalccsinstitute.com/resources/multimedia-library/ccs-commercial-and-regulatory-frameworks-lessons-learned-from-ccs-front-runners-in-norway/

Gong, W., Remiezowicz, E., Fosbøl, P., & von Solms, N. (2022). Design and Analysis of Novel CO2 Conditioning Process in Ship-Based CCS. *Energies*, *15*, 5928. https://doi.org/10.3390/en15165928

Govindan, K., Fattahi, M., & Keyvanshokooh, E. (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. *European Journal of Operational Research*, *263*(1), 108–141. https://doi.org/10.1016/j.ejor.2017.04.009

Guba, E., & Lincoln, Y. (1994). *Competing paradigms in qualitative research*. https://www.semanticscholar.org/paper/Competing-paradigms-in-qualitative-research.-Guba-Lincoln/f4ee6f7b09f4b1c9943cc36a8aa5a6391e1a92cf

Gurobi. (n.d.-a). *Academic Program and Licenses*. Gurobi Optimization. Retrieved May 29, 2023, from https://www.gurobi.com/academia/academic-program-and-licenses/

Gurobi. (n.d.-b). *Gurobi Optimizer*. Gurobi Optimization. Retrieved May 29, 2023, from https://www.gurobi.com/solutions/gurobi-optimizer/

Gurobi. (n.d.-c). *MIPGap—Gurobi Optimization*. Retrieved May 29, 2023, from https://www.gurobi.com/documentation/9.5/refman/mipgap2.html

Hadri, N., Viet Quang, D., Goetheer, E., & Abu Zahra, M. (2016). Aqueous amine solution characterization for post-combustion CO2 capture process. *Applied Energy*, *185*. https://doi.org/10.1016/j.apenergy.2016.03.043

Hajiaghaei-Keshteli, M., & Fathollahi Fard, A. M. (2019). Sustainable closed-loop supply chain network design with discount supposition. *Neural Computing and Applications*, *31*(9), 5343–5377. https://doi.org/10.1007/s00521-018-3369-5

Halsfund Oslo Celsio. (2023). *Personal Communication* [Personal communication].

Han, C., Zahid, U., An, J., Kim, K., & Kim, C. (2015). CO2 transport: Design considerations and project outlook. *Current Opinion in Chemical Engineering*, *10*, 42–48. https://doi.org/10.1016/j.coche.2015.08.001

Han, J.-H., & Lee, I.-B. (2012). Multiperiod Stochastic Optimization Model for Carbon Capture and Storage Infrastructure under Uncertainty in CO2 Emissions, Product Prices, and Operating Costs. *Industrial & Engineering Chemistry Research*, *51*(35), 11445–11457. https://doi.org/10.1021/ie3004754

Hasan, M. M. F., First, E. L., Boukouvala, F., & Floudas, C. A. (2015). A multi-scale framework for CO2 capture, utilization, and sequestration: CCUS and CCU. *Computers & Chemical Engineering*, *81*, 2–21. https://doi.org/10.1016/j.compchemeng.2015.04.034

Hasan, M. M. F., Zantye, M. S., & Kazi, M.-K. (2022). Challenges and opportunities in carbon capture, utilization and storage: A process systems engineering perspective. *Computers & Chemical Engineering*, *166*, 107925. https://doi.org/10.1016/j.compchemeng.2022.107925

HeidelbergCement. (n.d.). *Groundbreaking Technologies: CCU/S – Carbon Capture, Utilisation and Storage*. https://www.heidelbergmaterials.com/sites/default/files/assets/document/cc/6d/heidelbergcement-factsheet-ccus.pdf

HeidelbergCement. (2019, December 11). *Cement Producers have founded an Oxyfuel Research Corporation*. Heidelberg Materials. https://www.heidelbergmaterials.com/en/pr-11-12-2019

Herzog, H. (2016, May). *Lessons learned from CCS demonstration and large pilot projects*. Main. https://energy.mit.edu/publication/lessons-learned-from-ccs-demonstration-and-large-pilot-projects/

Herzog, H., Meldon, J., & Hatton, A. (2009). *Advanced Post-Combustion CO2 Capture*.

Horisont Energi. (n.d.). *Barents Blue*. Horisont Energi. Retrieved May 31, 2023, from https://horisontenergi.no/projects/barents-blue/

Hosseini, S. A., Lashgari, H., Choi, J. W., Nicot, J.-P., Lu, J., & Hovorka, S. D. (2013). Static and dynamic reservoir modeling for geological CO2 sequestration at Cranfield, Mississippi, U.S.A. *International Journal of Greenhouse Gas Control*, *18*, 449–462. https://doi.org/10.1016/j.ijggc.2012.11.009

Hydro. (2022a, January 19). *Developing carbon capture and storage technology for aluminium smelters*. https://www.hydro.com/en-NO/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminium-production/developing-carbon-capture-and-storage-technology-for-aluminium-smelters/

Hydro. (2022b, September 29). *Hydro's roadmap to zero-emission aluminium production*. https://www.hydro.com/en-NO/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminium-production/

IEA. (n.d.). *About*. IEA. Retrieved May 22, 2023, from https://www.iea.org/about

IEA. (2006). *In support of the G8 Plan of Action* (pp. 15–198). OECD. https://doi.org/10.1787/9789264042216-1-en

IEA. (2016). *CO2 Emissions from Fuel Combustion Highlights 2016*.

IEA. (2020a). Energy Technology Perspectives 2020. *Energy Technology Perspectives*.

IEA. (2019). *Is carbon capture too expensive? – Analysis*. IEA. https://www.iea.org/commentaries/is-carbon-capture-too-expensive

IEA. (2020b). *Regional opportunities – CCUS in Clean Energy Transitions – Analysis*. IEA. https://www.iea.org/reports/ccus-in-clean-energy-transitions/regional-opportunities

IEA. (2022, September). *Aluminium – Analysis*. IEA. https://www.iea.org/reports/aluminium

IEA GHG. (2008). *CO2 capture in the cement industry*. https://ieaghg.org/docs/General_Docs/Reports/2008-3.pdf

IEA GHG. (2013). *Deployment of CCS in the cement industry*. https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf

IEA GHG. (2018). *Cost of CO2 Capture in the Industrial Sector: Cement and Iron and Steel Industries*. https://ieaghg.org/publications/technical-reports/reports-list/10-technical-reviews/931-2018-tr03-cost-of-co2-capture-in-the-industrial-sector-cement-and-iron-and-steel-industries

IEAGHG. (2020). *The Status and Challenges of CO2 Shipping Infrastructures*. https://ieaghg.org/ccs-resources/blog/new-ieaghg-report-the-status-and-challenges-of-co2-shipping-infrastructures

International Aluminium. (2021). *Greenhouse Gas Emissions—Aluminium Sector*. International Aluminium Institute. https://international-aluminium.org/statistics/greenhouse-gas-emissions-aluminium-sector/

IOGP. (2023). *Map of CCUS Projects in Europe*. https://iogpeurope.org/wp-content/uploads/2022/11/Map-of-EU-CCUS-Projects.pdf?_gl=1*pmrxwl*_ga*NzE1MjA4MjY3LjE2ODU1NDE2MjM.*_up*MQ..

IPCC. (n.d.). *About—IPCC*. Retrieved May 16, 2023, from https://www.ipcc.ch/about/

IPCC. (2005). *IPCC special report on carbon dioxide capture and storage*. Cambridge University Press, for the Intergovernmental Panel on Climate Change.

IPCC. (2007). *Climate change 2007: Mitigation of climate change: contribution of Working Group III to the Fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC. (2015). *Climate change 2014: Synthesis report*. Intergovernmental Panel on Climate Change.

IPCC. (2018). *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press. https://doi.org/10.1017/9781009157940

Kalyanarengan Ravi, N., Van Sint Annaland, M., Fransoo, J. C., Grievink, J., & Zondervan, E. (2017). Development and implementation of supply chain optimization framework for CO2 capture and storage in the Netherlands. *Computers & Chemical Engineering*, *102*, 40–51. https://doi.org/10.1016/j.compchemeng.2016.08.011

Karayannis, V., Charalampides, G., & Lakioti, E. (2014). Socio-economic Aspects of CCS Technologies. *Procedia Economics and Finance*, *14*, 295–302. https://doi.org/10.1016/S2212-5671(14)00716-3

Karlsson, C. (Ed.). (2008). *Researching Operations Management*. Routledge. https://doi.org/10.4324/9780203886816

Kim, C., Kim, K., Kim, J., Ahmed, U., & Han, C. (2018). Practical deployment of pipelines for the CCS network in critical conditions using MINLP modelling and optimization: A case study of South Korea. *International Journal of Greenhouse Gas Control*, *73*, 79–94. https://doi.org/10.1016/j.ijggc.2018.03.024

Kjärstad, J., Ramdani, R., Gomes, P. M., Rootzén, J., & Johnsson, F. (2011). Establishing an integrated CCS transport infrastructure in northern Europe–Challenges and possibilities. *Energy Procedia*, *4*, 2417–2424. https://doi.org/10.1016/j.egypro.2011.02.135

Kjärstad, J., Skagestad, R., Eldrup, N. H., & Johnsson, F. (2016). Ship transport—A low cost and low risk CO2 transport option in the Nordic countries. *International Journal of Greenhouse Gas Control*, *54*, 168–184. https://doi.org/10.1016/j.ijggc.2016.08.024

Klokk, Ø., Schreiner, P. F., Pagès-Bernaus, A., & Tomasgard, A. (2010). Optimizing a CO2 value chain for the Norwegian Continental Shelf. *Energy Policy*, *38*(11), 6604–6614. https://doi.org/10.1016/j.enpol.2010.06.031

Koelbl, B. S., van den Broek, M. A., van Ruijven, B. J., Faaij, A. P. C., & van Vuuren, D. P. (2014). Uncertainty in the deployment of Carbon Capture and

Storage (CCS): A sensitivity analysis to techno-economic parameter uncertainty. *International Journal of Greenhouse Gas Control*, *27*, 81–102. https://doi.org/10.1016/j.ijggc.2014.04.024

Kumar, P. H., & Mageshvaran, D. R. (2020). *Methods And Solvers Used For Solving Mixed Integer Linear Programming And Mixed Nonlinear Programming Problems: A Review*. *9*(01).

Kumar, R. (2018). *Research Methodology: A Step-by-Step Guide for Beginners*. SAGE.

Kuo, J. Y. J., Romero, D. A., Beck, J. C., & Amon, C. H. (2016). Wind farm layout optimization on complex terrains – Integrating a CFD wake model with mixed-integer programming. *Applied Energy*, *178*, 404–414. https://doi.org/10.1016/j.apenergy.2016.06.085

Lahri, V., Shaw, K., & Ishizaka, A. (2021). Sustainable supply chain network design problem: Using the integrated BWM, TOPSIS, possibilistic programming, and ε-constrained methods. *Expert Systems with Applications*, *168*, 114373. https://doi.org/10.1016/j.eswa.2020.114373

Lee, S.-Y., Lee, J.-U., Lee, I.-B., & Han, J. (2017). Design under uncertainty of carbon capture and storage infrastructure considering cost, environmental impact, and preference on risk. *Applied Energy*, *189*, 725–738. https://doi.org/10.1016/j.apenergy.2016.12.066

Lee, U., Yang, S., Jeong, Y. S., Lim, Y., Lee, C. S., & Han, C. (2012). Carbon Dioxide Liquefaction Process for Ship Transportation. *Industrial & Engineering Chemistry Research*, *51*(46), 15122–15131. https://doi.org/10.1021/ie300431z

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., & Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, *61*, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020

Leeson, D., Ramirez, A., & Dowell, N. (2019). *Chapter 9. Carbon Capture and Storage from Industrial Sources* (pp. 296–314). https://doi.org/10.1039/9781788012744-00296

Leiss, W., & Krewski, D. (2019). Environmental scan and issue awareness: Risk management challenges for CCS. *International Journal of Risk Assessment* *and Management*, *22*, 234. https://doi.org/10.1504/IJRAM.2019.103340

Leonzio, G., Foscolo, P. U., & Zondervan, E. (2019). Sustainable utilization and storage of carbon dioxide: Analysis and design of an innovative supply chain. *Computers & Chemical Engineering*, *131*, 106569. https://doi.org/10.1016/j.compchemeng.2019.106569

Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, *39*, 426–443. https://doi.org/10.1016/j.rser.2014.07.093

Liu, E., Lu, X., & Wang, D. (2023). A Systematic Review of Carbon Capture, Utilization and Storage: Status, Progress and Challenges. *Energies*, *16*(6), Article 6. https://doi.org/10.3390/en16062865

L′Orange Seigo, S., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, *38*, 848–863. https://doi.org/10.1016/j.rser.2014.07.017

Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. *Journal of Cleaner Production*, *266*, 121994. https://doi.org/10.1016/j.jclepro.2020.121994

Manzolini, G., Giuffrida, A., Cobden, P. D., van Dijk, H. A. J., Ruggeri, F., & Consonni, F. (2020). Techno-economic assessment of SEWGS technology when applied to integrated steel-plant for CO2 emission mitigation. *International Journal of Greenhouse Gas Control*, *94*, 102935. https://doi.org/10.1016/j.ijggc.2019.102935

Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. *One Earth*, *4*(11), 1569–1584. https://doi.org/10.1016/j.oneear.2021.10.002

Martins, C. L., & Pato, M. V. (2019). Supply chain sustainability: A tertiary literature review. *Journal of Cleaner Production*, *225*, 995–1016. https://doi.org/10.1016/j.jclepro.2019.03.250

Mathisen, A., Normann, F., Biermann, M., Skagestad, R., & Haug, A. T. (2019). *CO2 Capture Opportunities in the Norwegian Silicon Industry*. SINTEF Academic Press. https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2637936

McLaughlin, H., Littlefield, A. A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B. K., Bazilian, M. D., Kim, J., & Griffiths, S. (2023). Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world. *Renewable and Sustainable Energy Reviews*, *177*, 113215. https://doi.org/10.1016/j.rser.2023.113215

Meerman, J. C., Hamborg, E. S., van Keulen, T., Ramírez, A., Turkenburg, W. C., & Faaij, A. P. C. (2012). Techno-economic assessment of CO2 capture at steam methane reforming facilities using commercially available technology. *International Journal of Greenhouse Gas Control*, *9*, 160–171. https://doi.org/10.1016/j.ijggc.2012.02.018

Melien, T. (2005). Economic and Cost Analysis for CO2 Capture Costs in The CO2 Capture Project Scenarios. In *Carbon Dioxide Capture for Storage in Deep Geologic Formations-Results from the CO Capture Project2* (Vol. 1, pp. 47–87). https://doi.org/10.1016/B978-008044570-0/50088-X

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining Supply Chain Management. *Journal of Business Logistics*, *22*(2), 1–25. https://doi.org/10.1002/j.2158-1592.2001.tb00001.x

Metz, B., Davidson, O., Coninck, H. de, Loos, M., & Meyer, L. (2005). *Carbon Dioxide Capture and Storage—IPCC*. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

Middleton, R. S., & Bielicki, J. M. (2009a). A comprehensive carbon capture and storage infrastructure model. *Energy Procedia*, *1*(1), 1611–1616. https://doi.org/10.1016/j.egypro.2009.01.211

Middleton, R. S., & Bielicki, J. M. (2009b). A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy*, *37*(3), 1052–1060. https://doi.org/10.1016/j.enpol.2008.09.049

Middleton, R. S., Kuby, M. J., Wei, R., Keating, G. N., & Pawar, R. J. (2012). A dynamic model for optimally phasing in CO2 capture and storage infrastructure. *Environmental Modelling & Software*, *37*, 193–205. https://doi.org/10.1016/j.envsoft.2012.04.003

Mission Possible Partnership. (2021). *Closing the gap for aluminium emissions: Technologies to accelerate deep decarbonization of direct emissions*.

Mitsubishi. (2002). *Carbon dioxide handling involves using liquefied petroleum gas ship for conveying carbon dioxide* (Patent No. JP2004125039-A).

Mitsubishi. (2004). *Ship transport of CO2*. https://ieaghg.org/docs/General_Docs/Reports/PH4-

30%20Ship%20Transport.pdf

Morbee, J., Serpa, J., & Tzimas, E. (2012). Optimised deployment of a European CO2 transport network. *International Journal of Greenhouse Gas Control*, *7*, 48–61. https://doi.org/10.1016/j.ijggc.2011.11.011

Munkejord, S. T., Hammer, M., & Løvseth, S. W. (2016). CO2 transport: Data and models – A review. *Applied Energy*, *169*, 499–523. https://doi.org/10.1016/j.apenergy.2016.01.100

Nam, H., Lee, T., Lee, J., Lee, J., & Chung, H. (2013). Design of carrier-based offshore CCS system: Plant location and fleet assignment. *International Journal of Greenhouse Gas Control*, *12*, 220–230. https://doi.org/10.1016/j.ijggc.2012.10.002

Neele, F., de Kler, R., Nienoord, M., Brownsort, P., Koornneef, J., Belfroid, S., Peters, L., van Wijhe, A., & Loeve, D. (2017). CO2 Transport by Ship: The Way Forward in Europe. *Energy Procedia*, *114*, 6824–6834. https://doi.org/10.1016/j.egypro.2017.03.1813

Nemitallah, M. A., Habib, M. A., Badr, H. M., Said, S. A., Jamal, A., Ben-Mansour, R., Mokheimer, E. M. A., & Mezghani, K. (2017). Oxy-fuel combustion technology: Current status, applications, and trends. *International Journal of Energy Research*, *41*(12), 1670–1708. https://doi.org/10.1002/er.3722

NETL. (2022, July 15). *Cost of Capturing CO2 from Industrial Sources*. Netl.Doe.Gov. https://www.netl.doe.gov/energy-analysis/details?id=865aaad2-9252-44d9-a48a-95599b3072b4&fbclid=IwAR2A_nHbRbbcojF3p6HYtqkD8iihYThAQkRJjaBL__arzjLQ-Ejqqch8RKg

Newell, P., & Ilgen, A. G. (2019). Chapter 1—Overview of Geological Carbon Storage (GCS). In P. Newell & A. G. Ilgen (Eds.), *Science of Carbon Storage in Deep Saline Formations* (pp. 1–13). Elsevier. https://doi.org/10.1016/B978-0-12-812752-0.00001-0

Nie, Z., Korre, A., Elahi, N., & Durucan, S. (2017). Real Options Analysis of CO2 Transport and Storage in the UK Continental Shelf under Geological and Market Uncertainties and the Viability of Subsidies for Market Development. *Energy Procedia*, *114*, 6612–6622. https://doi.org/10.1016/j.egypro.2017.03.1815

NOAA. (2023a, April 5). *Greenhouse gases continued to increase rapidly in 2022*. https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-2022

NOAA. (2023b, May 12). *Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov*. http://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Nordic CCS Competence Center. (2015, November). *Industrial implementation of Carbon Capture in Nordic industry sectors*. SINTEF. https://www.sintef.no/en/publications/publication/1308897/

Norske Utslipp. (n.d.). *The Norwegian PRTR - Pollutants to air and water and generated transfers of waste*. Retrieved May 22, 2023, from https://www.norskeutslipp.no/en/Articles/About-Norske-Utslipp/

Norskpetroleum. (2023a, March 21). *Carbon capture and storage*. Norwegianpetroleum.No. https://www.norskpetroleum.no/en/environment-and-technology/carbon-capture-and-storage/

Norskpetroleum. (2023b, March 21). *Fangst, transport og lagring av CO2—Norskpetroluem.no*. Norskpetroleum.No. https://www.norskpetroleum.no/miljo-og-teknologi/fangst-transport-og-lagring-av-co2/

Northern Lights. (n.d.-a). *Northern Lights – About the Longship project*. Retrieved May 22, 2023, from https://norlights.com/about-the-longship-project/

Northern Lights. (n.d.-b). *Northern Lights – What we do*. Retrieved May 31, 2023, from https://norlights.com/what-we-do/

Northern Lights. (n.d.-c). *Northern Lights – Who we are*. Retrieved May 22, 2023, from https://norlights.com/who-we-are/

Norwegian Environemen Agency. (2021). *The Norwegian PRTR - Pollutants to air and water and generated transfers of waste, Carbon dioxide fossil*. https://www.norskeutslipp.no/en/Components/Emission/Carbon-dioxide-fossil/?ComponentType=utslipp&ComponentPageID=180&SectorID=600

Norwegian Ministry of Climate and Environment. (2021). *Norway's Climate Action Plan for 2021–2030*. https://www.regjeringen.no/contentassets/a78ecf5ad2344fa5ae4a394412ef8975/en-gb/pdfs/stm202020210013000engpdfs.pdf

Norwegian Ministry of Petroleum and Energy. (n.d.). *Carbon capture and storage—CCS* [Tema]. Government.No; regjeringen.no. Retrieved May 19, 2023, from https://www.regjeringen.no/en/topics/energy/carbon-capture-and-storage/id86982/

OGCI, Global CCS Institute, & STOREGGA. (2022). *CO2 Storage Resource Catalogue Cycle 3 Report* (p. 31). https://www.ogci.com/wp-content/uploads/2022/03/CSRC_Cycle_3_Main_Report_Final.pdf

Øi, L. E., Eldrup, N., Adhikari, U., Bentsen, M. H., Badalge, J. L., & Yang, S. (2016). Simulation and Cost Comparison of CO2 Liquefaction. *Energy Procedia*, *86*, 500–510. https://doi.org/10.1016/j.egypro.2016.01.051

Omoregbe, O., Mustapha, A. N., Steinberger-Wilckens, R., El-Kharouf, A., & Onyeaka, H. (2020). Carbon capture technologies for climate change mitigation: A bibliometric analysis of the scientific discourse during 1998–2018. *Energy Reports*, *6*, 1200–1212. https://doi.org/10.1016/j.egyr.2020.05.003

Onyebuchi, V. E., Kolios, A., Hanak, D. P., Biliyok, C., & Manovic, V. (2018). A systematic review of key challenges of CO2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, *81*, 2563–2583. https://doi.org/10.1016/j.rser.2017.06.064

OpenSolver. (n.d.). *Guide to Solvers – OpenSolver for Excel*. Retrieved May 29, 2023, from https://opensolver.org/guide-to-solvers/

Orchard, K., Hay, M., Ombudstvedt, I., Skagestad, R., Joos, M., Nysæter, G., Sjøbris, C., Gimnes Jarøy, A., Durusut, E., & Craig, J. (2021). *The Status and Challenges of CO2 Shipping Infrastructures* (SSRN Scholarly Paper No. 3820877). https://doi.org/10.2139/ssrn.3820877

Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: A review. *Environmental Chemistry Letters*, *19*(2), 797–849. https://doi.org/10.1007/s10311-020-01133-3

Ozaki, M., Ohsumi, T., & Kajiyama, R. (2013). Ship-based Offshore CCS Featuring CO2 Shuttle Ships Equipped with Injection Facilities. *Energy Procedia*, *37*, 3184–3190. https://doi.org/10.1016/j.egypro.2013.06.205

Parvizi, M., Shadkam, E., & Jahani, N. (2015). A Hybrid COA/ε-Constraint Method for Solving Multi-Objective Problems. *International Journal in Foundations of Computer Science & Technology*, *5*, 27–40. https://doi.org/10.5121/ijfcst.2015.5503

Pearson, P., & Cousins, A. (2016). 18—Assessment of corrosion in amine-based post-combustion capture of carbon dioxide systems. In P. H. M. Feron (Ed.), *Absorption-Based Post-combustion Capture of Carbon Dioxide* (pp. 439–

463). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100514-9.00018-4

Pires, J., Martins, F., Alvim-Ferraz, M. C. M., & Simões, M. (2011). Recent developments on carbon capture and storage: An overview. *Chemical Engineering Research & Design - CHEM ENG RES DES*, *89*, 1446–1460. https://doi.org/10.1016/j.cherd.2011.01.028

Pishvaee, M. S., Kianfar, K., & Karimi, B. (2010). Reverse logistics network design using simulated annealing. *The International Journal of Advanced Manufacturing Technology*, *47*(1), 269–281. https://doi.org/10.1007/s00170-009-2194-5

Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2012). Robust possibilistic programming for socially responsible supply chain network design: A new approach. *Fuzzy Sets and Systems*, *206*, 1–20. https://doi.org/10.1016/j.fss.2012.04.010

Ragab, M., & Arisha, A. (2018). Research Methodology in Business: A Starter's Guide. *Management and Organizational Studies*, *5*. https://doi.org/10.5430/mos.v5n1p1

Raza, A., Gholami, R., Rezaee, R., Rasouli, V., & Rabiei, M. (2018). Significant Aspects of Carbon Capture and Storage – A Review. *Petroleum*, *5*. https://doi.org/10.1016/j.petlm.2018.12.007

Raza, A., Rezaee, R., Gholami, R., Bing, C. H., Nagarajan, R., & Hamid, M. A. (2016). A screening criterion for selection of suitable CO 2 storage sites. *Journal of Natural Gas Science and Engineering*, *28*, 317–327. https://doi.org/10.1016/j.jngse.2015.11.053

Riviera. (2022, November 11). *Northern Lights drilling confirms capacity for CO2 storage*. Riviera. https://www.rivieramm.com/news-content-hub/news-content-hub/northern-lights-drilling-confirms-capacity-for-co2-storage-73741

Romasheva, N., & Ilinova, A. (2019). CCS Projects: How Regulatory Framework Influences Their Deployment. *Resources*, *8*(4), Article 4. https://doi.org/10.3390/resources8040181

Rosenzweig, C., Casassa, G., Karoly, D., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T., Seguin, B., & Tryjanowski, P. (2007). *Assessment of observed changes and responses in natural and managed systems*. https://doi.org/10.5167/uzh-33180

Roussanaly, S., Hognes, E. S., & Jakobsen, J. P. (2013). Multi-criteria Analysis of Two CO2 Transport Technologies. *Energy Procedia*, *37*, 2981–2988. https://doi.org/10.1016/j.egypro.2013.06.184

Roussanaly, S., Jakobsen, J. P., Hognes, E. H., & Brunsvold, A. L. (2013). Benchmarking of CO2 transport technologies: Part I—Onshore pipeline and shipping between two onshore areas. *International Journal of Greenhouse Gas Control*, *19*, 584–594. https://doi.org/10.1016/j.ijggc.2013.05.031

Roussanaly, S., Skaugen, G., Aasen, A., Jakobsen, J., & Vesely, L. (2017). Techno-economic evaluation of CO2 transport from a lignite-fired IGCC plant in the Czech Republic. *International Journal of Greenhouse Gas Control*, *65*, 235–250. https://doi.org/10.1016/j.ijggc.2017.08.022

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control*, *40*, 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018

Saeedi, A., & Rezaee, R. (2012). Effect of residual natural gas saturation on multiphase flow behaviour during CO2 geo-sequestration in depleted natural gas reservoirs. *Journal of Petroleum Science and Engineering*, *82–83*, 17–26. https://doi.org/10.1016/j.petrol.2011.12.012

Saunders, M., Lewis, P., & Thornhill, A. (2016). *Research Methods for Business Students* (seventh). Pearson.

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (Eighth Edition). Pearson.

Serpa, J., Morbee, J., & Tzimas, E. (2011). Technical and economic characteristics of a CO2 transmission pipeline infraestructure. *JRC62502*, 1–43.

Shen, Z.-J. max. (2006). Integrated supply chain design models: A survey and future research directions. *Journal of Industrial and Management Optimization*, *3*(1), 1–27. https://doi.org/10.3934/jimo.2007.3.1

Simchi-Levi, D., Kaminsky, P. M., & Simchi-Levi, E. (2003, November 22). *Managing the Supply Chain: The Definitive Guide for the Business Professional*. https://www.semanticscholar.org/paper/Managing-the-Supply-Chain%3A-The-Definitive-Guide-for-Simchi-Levi-Kaminsky/5a95a0fa2622d8746fe5804e0b0eebc726aa91d9

SINTEF. (n.d.). *About SINTEF - Applied research, technology and innovation*. SINTEF. Retrieved May 22, 2023, from https://www.sintef.no/en/sintef-group/this-is-sintef/

SINTEF, Element Energy, TNO, Engineering Brevik, & Polarkonsult. (2018, November). *Shipping carbon dioxide (CO2): UK cost estimation study*. GOV.UK. https://www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study

Soleimani, H., & Kannan, G. (2015). A hybrid particle swarm optimization and genetic algorithm for closed-loop supply chain network design in large-scale networks. *Applied Mathematical Modelling*, *39*(14), 3990–4012. https://doi.org/10.1016/j.apm.2014.12.016

Solomon, S., Carpenter, M., & Flach, T. A. (2008). Intermediate storage of carbon dioxide in geological formations: A technical perspective. *International Journal of Greenhouse Gas Control*, *2*(4), 502–510. https://doi.org/10.1016/j.ijggc.2008.04.004

Stake, R. E. (1995). *The art of case study research*. Sage Publications.

Stanger, R., Wall, T., Spörl, R., Paneru, M., Grathwohl, S., Weidmann, M., Scheffknecht, G., McDonald, D., Myöhänen, K., Ritvanen, J., Rahiala, S., Hyppänen, T., Mletzko, J., Kather, A., & Santos, S. (2015). Oxyfuel combustion for CO2 capture in power plants. *International Journal of Greenhouse Gas Control*, *40*, 55–125. https://doi.org/10.1016/j.ijggc.2015.06.010

Statistics Norway. (2022). *Emissions to air*. SSB. https://www.ssb.no/en/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft

Statistics Norway. (2023). *Electricity*. SSB. https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitet

Stolaroff, J. K., Pang, S. H., Li, W., Kirkendall, W. G., Goldstein, H. M., Aines, R. D., & Baker, S. E. (2021). Transport Cost for Carbon Removal Projects With Biomass and CO2 Storage. *Frontiers in Energy Research*, *9*. https://www.frontiersin.org/articles/10.3389/fenrg.2021.639943

Svensson, R., Odenberger, M., Johnsson, F., & Strömberg, L. (2005). - Transportation infrastructure for CCS —Experiences and expected development. In E. S. Rubin, D. W. Keith, C. F. Gilboy, M. Wilson, T. Morris, J. Gale, & K. Thambimuthu (Eds.), *Greenhouse Gas Control Technologies 7* (pp. 2531–2534). Elsevier Science Ltd. https://doi.org/10.1016/B978-008044704-9/50367-0

Tapia, J. F. D., Lee, J.-Y., Ooi, R. E. H., Foo, D. C. Y., & Tan, R. R. (2018). A review of optimization and decision-making models for the planning of CO

2 capture, utilization and storage (CCUS) systems. *Sustainable Production and Consumption*, *13*, 1–15. https://doi.org/10.1016/j.spc.2017.10.001

Technology Centre Mongstad. (n.d.). *Technology Centre Mongstad | Test centre for CO2 capture*. Retrieved May 22, 2023, from https://tcmda.com/about-tcm/

Theo, W. L., Lim, J. S., Hashim, H., Mustaffa, A. A., & Ho, W. S. (2016). Review of pre-combustion capture and ionic liquid in carbon capture and storage. *Applied Energy*, *183*(C), 1633–1663.

Tock, L., & Maréchal, F. (2013). Process engineering method for systematically comparing CO2 capture options. In A. Kraslawski & I. Turunen (Eds.), *Computer Aided Chemical Engineering* (Vol. 32, pp. 367–372). Elsevier. https://doi.org/10.1016/B978-0-444-63234-0.50062-2

Turk, G. A., Cobb, T. B., Jankowski, D. J., Wolsky, A. M., & Sparrow, F. T. (1987). CO2 Transport: A new application of the assignment problem. *Energy*, *12*(2), 123–130. https://doi.org/10.1016/0360-5442(87)90116-2

UNFCCC. (n.d.). *The Paris Agreement | UNFCCC*. Retrieved May 16, 2023, from https://unfccc.int/process-and-meetings/the-paris-agreement

United Nations. (2015). *Paris Agreement*. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

USGS. (2022). *Silicon Statistics and Information*. https://www.usgs.gov/centers/national-minerals-information-center/silicon-statistics-and-information

Waltho, C., Elhedhli, S., & Gzara, F. (2019). Green supply chain network design: A review focused on policy adoption and emission quantification. *International Journal of Production Economics*, *208*, 305–318. https://doi.org/10.1016/j.ijpe.2018.12.003

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems*, *51*(2), 262–269. https://doi.org/10.1016/j.dss.2010.11.020

Wang, H., Chen, J., & Li, Q. (2019). A Review of Pipeline Transportation Technology of Carbon Dioxide. *IOP Conference Series. Earth and Environmental Science*, *310*(3). https://doi.org/10.1088/1755-1315/310/3/032033

Wang, P.-T., Wei, Y.-M., Yang, B., Li, J.-Q., Kang, J.-N., Liu, L.-C., Yu, B.-Y., Hou, Y.-B., & Zhang, X. (2020). Carbon capture and storage in China's power sector: Optimal planning under the 2 °C constraint. *Applied Energy*, *263*, 114694. https://doi.org/10.1016/j.apenergy.2020.114694

Wang, X., & Song, C. (2020). Carbon Capture From Flue Gas and the Atmosphere: A Perspective. *Frontiers in Energy Research*, *8*. https://www.frontiersin.org/articles/10.3389/fenrg.2020.560849

Wildbolz, C. (2009). *Life Cycle Assessment of Selected Technologies for CO 2 Transport and Sequestration*. https://www.semanticscholar.org/paper/Life-Cycle-Assessment-of-Selected-Technologies-for-Wildbolz/79a564375acaf5ed54cf664c9e2bcd613dc0cd37

Wiley, D. E., Ho, M. T., & Bustamante, A. (2011). Assessment of opportunities for CO2 capture at iron and steel mills: An Australian perspective. *Energy Procedia*, *4*, 2654–2661. https://doi.org/10.1016/j.egypro.2011.02.165

Wilkes, M. D., & Brown, S. (2022). Evaluating the flexible operation of vacuum-pressure swing adsorption for CO2 capture from modern gas turbines. In L. Montastruc & S. Negny (Eds.), *Computer Aided Chemical Engineering* (Vol. 51, pp. 427–432). Elsevier. https://doi.org/10.1016/B978-0-323-95879-0.50072-2

Will M. Bertrand, J., & Fransoo, J. C. (2002). Operations management research methodologies using quantitative modeling. *International Journal of Operations & Production Management*, *22*(2), 241–264. https://doi.org/10.1108/01443570210414338

Wintershall Dea. (2022, October 5). *Wintershall Dea awarded its first CO2 licence in Norway*. Wintershall Dea AG. https://wintershalldea.com/en/newsroom/wintershall-dea-awarded-its-first-co2-licence-norway

Yadav, S., & Mondal, S. (2021). A review on the progress and prospects of oxy-fuel carbon capture and sequestration (CCS) technology. *Fuel*, *308*, 122057. https://doi.org/10.1016/j.fuel.2021.122057

Yang, L., Zhang, X., & McAlinden, K. J. (2016). The effect of trust on people's acceptance of CCS (carbon capture and storage) technologies: Evidence from a survey in the People's Republic of China. *Energy*, *96*, 69–79. https://doi.org/10.1016/j.energy.2015.12.044

Yoo, B.-Y., Choi, D.-K., Kim, H.-J., Moon, Y.-S., Na, H.-S., & Lee, S.-G. (2013). Development of CO2 terminal and CO2 carrier for future commercialized CCS market. *International Journal of Greenhouse Gas Control*, *12*, 323–

332. https://doi.org/10.1016/j.ijggc.2012.11.008

Yue, D., Gong, J., & You, F. (2015, April 14). *Synergies between Geological Sequestration and Microalgae Biofixation for Greenhouse Gas Abatement: Life Cycle Design of Carbon Capture, Utilization, and Storage Supply Chains* (world) [Research-article]. ACS Publications; American Chemical Society. https://doi.org/10.1021/sc5008253

Zahid, U., An, J., Lee, C.-J., Lee, U., & Han, C. (2015). Design and Operation Strategy of CO2 Terminal. *Industrial & Engineering Chemistry Research*, *54*(8), 2353–2365. https://doi.org/10.1021/ie503696x

Zamarripa, M. A., Eslick, J. C., Matuszewski, M. S., & Miller, D. C. (2018). Multi-objective Optimization of Membrane-based CO2 Capture. In M. R. Eden, M. G. Ierapetritou, & G. P. Towler (Eds.), *Computer Aided Chemical Engineering* (Vol. 44, pp. 1117–1122). Elsevier. https://doi.org/10.1016/B978-0-444-64241-7.50181-6

Zapantis, A., Townsend, A., & Rassool, D. (2019). *Policy priorities to incentivise large scale development of CCS*. https://www.globalccsinstitute.com/wp-content/uploads/2020/04/TL-Report-Policy-options-for-CCS-investment-digital.pdf

Zeipen, I. (2020). *Key enablers and hurdles impacting CCUS deployment with an assessment of current activities to address these issues*.

ZEP. (n.d.). *CCS/CCU projects*. Zero Emissions Platform. Retrieved May 31, 2023, from https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/

ZEP. (2011). *The costs of CO2 transport: Post-demonstration CCS in the EU*. Global CCS Institute. https://www.globalccsinstitute.com/resources/publications-reports-research/the-costs-of-co2-transport-post-demonstration-ccs-in-the-eu/

Zhang, S., Zhuang, Y., Liu, L., Zhang, L., & Du, J. (2020). Optimization-based approach for CO2 utilization in carbon capture, utilization and storage supply chain. *Computers & Chemical Engineering*, *139*, 106885. https://doi.org/10.1016/j.compchemeng.2020.106885

Zhao, S., Feron, P. H. M., Deng, L., Favre, E., Chabanon, E., Yan, S., Hou, J., Chen, V., & Qi, H. (2016). Status and progress of membrane contactors in post-combustion carbon capture: A state-of-the-art review of new developments. *Journal of Membrane Science*, *511*, 180–206. https://doi.org/10.1016/j.memsci.2016.03.051

Appendices

Appendix 1. Interview guide

A. Group 1: Technical experts in each component of CCS in Norway

A.1. Introduction

1. Introduction of the interviewers and about the thesis
2. The purpose of the interview

A.2. Interviewee background

1. Currently, you are working at company XXX. Could you describe your role and experience in the organization regarding CCS?

A.3. Questions about each process in CCS

A.3.1. For capture process

1. Could you give an overview about CO_2 capture in Norway?
2. Could you elaborate on important factors affecting CO_2 capture in Norway?
3. In our study, we will consider some sectors such as refinery, iron and steel, aluminum, or cement, how can we choose suitable capture technology for each sector?
4. We have found some numbers about unitary capture cost in Europe from literature (as attached file sent in the interview). Do you think these numbers can be applied under the Norwegian context?

   Follow-up:

   a. If not, could you enlighten us about unitary capture costs in Norway?
   b. Could you suggest us some sources to find relevant capture cost for Norway?
   c. Could you provide us information about the potential to reduce capture costs for different sectors in Norway?
5. To further examine this topic, who would you recommend that we can talk to?

A.3.2. For transport process

1. What are available CO_2 transport technologies in Norway recently?

   Follow-up:

   a. Are there any relevant projects you could name here?
2. What do you think are the factors to consider when using different modes for CO_2 transportation?

3. How do you evaluate the potential to install a pipeline network for CO_2 transportation in Norway? What are the difficulties of implementing such a network?
4. We have found some numbers about unitary transport cost for pipeline, ship, and truck transport from literature (as attached file sent in the interview). Do you think these numbers can be applied in Norway?

   Follow-up:
   a. (In case the interviewees conducted their own cost estimation) Do you consider different distance range (for truck transport) or different size (for ship and pipeline transport) when formulating the transport cost model? If yes, could you explain more about that?
   b. Could you suggest us some sources to find more data for Norway?
5. To further examine this topic, who would you recommend us to talk to?

A.3.3. For storage process

1. What are existing and planned storage sites in Norway recently?

   Follow-up:
   a. What are their storage technologies and capacities?
2. We found the unitary storage cost of 18 €/tCO_2 in Europe in literature, does this reflects the real situation in Norway?
3. To further examine this topic, who would you recommend that we can talk to?

B. Group 2: Experts in CCS market in Norway

B.1. Interview 1

B.1.1. Introduction

1. Introduction of the interviewers and about the thesis
2. The purpose of the interview: defining the problem

B.1.2. Interviewee background

1. Could you describe your role and experience in the organization regarding CCS?

B.1.3. CCS system in Norway

1. Could you give an overview about each element of the CCS system in Norway, including capture, transport, and storage?
2. Where would you recommend that we can find relevant information regarding CCS network in Norway?

B.2. Interview 2

B.2.1. Introduction

1. The purpose of the interview: mapping CCS system in Norway

B.2.2. Questions about CO_2 sources

1. How can we categorize types of Norwegian plants, such as steel, cement, power coal/gas, refinery, etc.?
2. We have found nearly 100 CO_2 sources reported in Norway, should we consider all these sources or just sources that meet a certain criterion?

   Follow-up:

   a. Some of these sources have already been involved in a CCS project, should we also consider them?

   b. In our list of CO_2 sources, offshore petroleum sites are one of the biggest CO_2 sources in Norway. However, we found little information regarding capturing CO_2 from these sites. Could you explain why?

B.2.3. Questions about transport process

1. What is the current status of CO_2 ship transport in Norway?

   Follow-up:

   a. Have CO_2 ship transport with offshore unloading been applied elsewhere yet?
2. How can we design pipeline routes?
3. Do you have any advice on where to find information about CO_2 truck transport?

B.2.4. Questions about storage process

1. Currently, there are many storage sites in Norway, such as Sleipner, Northern Lights, Barents Blue, Borg, Snøhvit and Smeaheia. How can we choose suitable storage sites?
2. We found the unitary storage cost of 18 €/tCO_2 in Europe in literature, does this reflects situation in Norway?

B.3. Interview 3

B.3.1. Introduction

1. The purpose of the interview: reviewing the collected data

B.3.2. Question

1. Does the data in each process of CCS supply chain make sense with the Norwegian situation?
2. Do you have any recommendations for us to improve the quality of the data?

C. Group 3: Experts in SCND for CCS at different scales

C.1. Introduction

1. Introduction of the interviewers and about the thesis
2. The purpose of the interview

C.2. Interviewee background

1. Could you describe your project and your role in the project?

C.3. Questions about the model

1. Could you explain more about your model to identify an optimal supply chain network for CCS?

   Follow-up:

   a. How did you categorize types of plant?
2. Which elements are important to consider when formulating cost functions for each process of CCS, namely capture, transport and storage?

   Follow-up:

   a. Why did you take into account discount rate when calculating levelized cost of stored and avoided carbon?
   b. Why is ship transport cost modelled based on flowrate and linear regression of distance and unitary cost, while pipeline transport cost is not?
   c. For ship transport, what is the meaning of buffer storage and how to choose suitable buffer storage?
   d. Why is maintenance transport cost equal to zero in your model?
3. Where would you suggest that we can find related data for cost of CO_2 capture, transport, and storage?

C.4. Questions about the software

1. Which software did you use to visualize maps and the results?
2. Which software did you use to run the model in your project? What are its disadvantages and advantages?

   Follow-up:

   a. Which software do you recommend us to solve our problem?

C.5. Other

1. To further examine this topic, who would you recommend that we can talk to?
2. Do you have any other recommendations for us before the end of this interview?

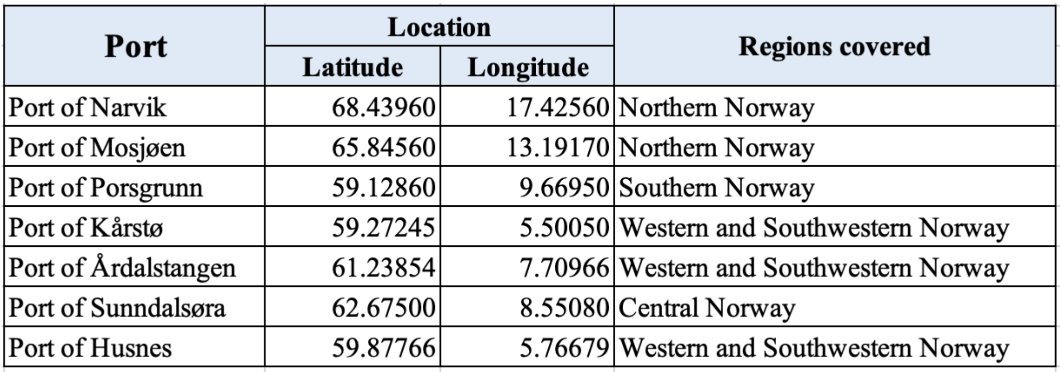
Appendix 2. CO_2 emissions of the considered plants

Node (N)	Name	Sector	Main activity	Location		Emissions (Mt CO2/year)	Share of CO2 emissions from land-based industry
				Latitude	Longtitude		
r1	Mongstad refinery	Refinery/Petrochemical	Production of refined petroleum products	60.80309221	5.02371971	1 997.74	15.40%
o1	Gassco AS Kårstø processing plant	Natural gas processing/Fertilizer	Extraction of natural gas	59.27513709	5.50716440	839.80	6.47%
c1	Heidelberg materials Brevik sementfabrikk	Cement	Production of cement	59.06106238	9.69061094	759.63	5.85%
a1	Hydro Aluminum Sunndal	Aluminium	Production of primary aluminium	62.67589825	8.55977958	652.78	5.03%
o2	Yara Porsgrunn	Natural gas processing/Fertilizer	Production of fertiliser, nitrogen compounds and growing soil	59.12514686	9.61934495	575.27	4.43%
a2	Hydro Aluminum Karmøy	Aluminium	Production of primary aluminium	59.31367985	5.31532086	445.00	3.43%
r2	Ineos Rafnes	Refinery/Petrochemical	Production of ethylene, polyeten, solder, PVC, and propylene products	59.09087752	9.59331017	442.00	3.41%
s1	Wacker Chemicals Norway	Silicon	Production of silicon and silica	63.31631714	9.14278993	413.00	3.18%
a3	Alcoa Norway AS Mosjøen	Aluminium	Production of primary aluminium	65.84923490	13.19250733	406.29	3.13%
s2	Elkem Salten	Silicon	Production of silicon and microsilica	67.36385541	15.58817551	348.58	2.69%
i1	Eramet Norway Sauda	Iron & Steel	Production of ferroalloys	59.64838523	6.36211056	348.44	2.69%
a4	Sør-Norge Aluminium	Aluminium	Production of primary aluminium	59.86689066	5.77093240	346.92	2.67%
a5	Hydro Aluminum Årdal Metallverk	Aluminium	Production of primary aluminium	61.23643303	7.70488934	327.00	2.52%
c2	Norcem Kjøpsvik	Cement	Production of cement	68.09366454	16.37106960	289.60	2.23%
i2	Finnfjord	Iron & Steel	Production of ferroalloys	69.22124874	18.07910459	288.58	2.22%
i3	Eramet Titanium & Iron	Iron & Steel	Production of iron and steel	60.11840092	6.55588281	275.64	2.12%
s3	Elkem Rana	Silicon	Production of ferrosilicon and microsilica	66.31530781	14.17611901	241.36	1.86%
s4	Elkem Bremanger	Silicon	Production of inoculants, microsilica and silicon powder	61.77081777	5.29668310	232.00	1.79%
i4	Eramet Norway Kvinesdal	Iron & Steel	Production of ferroalloys	58.27903614	6.89473178	231.33	1.78%
s5	Elkem Thamshavn	Silicon	Production of metallurgical silicon and microsilica	63.31693229	9.87155679	224.83	1.73%

Appendix 3. Chemical engineering plant cost index (CEPCI) (Chemical Engineering, 2020)

Year	CEPCI value
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	603.1
2019	607.5
2020	596.2

Appendix 4. List of ports



Port	Location		Regions covered
	Latitude	Longitude	
Port of Narvik	68.43960	17.42560	Northern Norway
Port of Mosjøen	65.84560	13.19170	Northern Norway
Port of Porsgrunn	59.12860	9.66950	Southern Norway
Port of Kårstø	59.27245	5.50050	Western and Southwestern Norway
Port of Årdalstangen	61.23854	7.70966	Western and Southwestern Norway
Port of Sunndalsøra	62.67500	8.55080	Central Norway
Port of Husnes	59.87766	5.76679	Western and Southwestern Norway