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LOG953 Petroleum Logistics

Pricing Natural Gas Value Chain Emissions

- A Scenario-based Case Study of the Norwegian Barents Sea

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Preface

This thesis represents the mandatory final part of our Master of Science Degree in Petroleum Logistics at Molde University College.

We would take the opportunity to thank our supervisor professor Arild Hervik for his excellent guidance and Katarina Shaton for her insight and assistance throughout the thesis.

Furthermore, we thank our families for their support.

Molde, May 2017.
Lasse H. Bekken & Fredrik S. Strømme

Summary

The maturing of the Norwegian continental shelf has led petroleum activities moving further north to look for additional resources. The Barents Sea is expected to hold around 65% of the total undiscovered resources on the NCS, and finding good transport solutions is stated to be key for further development. Gassco has recommended to identify measures to bridge the gap between socioeconomic and project economic perspectives for the transport infrastructure and our research aims to bridge this gap by focusing on the externality associated by CO_2 emissions.

The purpose of the study was to advance the understanding of the impact of carbon pricing on the emissions from future Norwegian natural gas supply from the Barents Sea to the European market. Through a carbon footprint analysis based on existing developments on the Norwegian continental shelf, we constructed hypothetical value chain scenarios to obtain the emission intensities for transporting natural from the Barents Sea to Europe. The result of the analysis showed that most emissions could be linked to power generation using turbine technology, and the fact that the gas had to be transported over great distances. However, findings also showed that the emissions could be significantly reduced given the source of energy used for power generation in the chains. Our analysis gave a unit emission intensity of 37,004 kg CO_2 per Sm^3 oe. on the best case scenario.

By investigating present and future carbon pricing policies in Norway and the EU we could put a price on the carbon footprints obtained in the analysis. The current carbon price the petroleum industry faced when transporting natural gas from the shelf to Europe was the summation of the Norwegian CO_2-tax and the EU - emission trading scheme. For the future carbon price, several reports and publications were reviewed and a carbon price which corresponded to the recent Paris Agreement of 2015 and the global two-degree target were applied. When putting a price on the emissions, the current cost on our best case scenario yield 18,32 NOK per Sm^3oe., while the two-degree carbon price gave a cost of 35,16 NOK per Sm^3oe.

With the emissions being priced per ton CO_2 released into the atmosphere from the value chain activities, it was a direct link between the carbon footprints and the cost the emissions. Meaning that the value chains with the lowest carbon footprints experienced the lowest cost of emissions.

Our findings could further highlight and strengthen four competitive advantages for the future Norwegian gas supply; (1) Long-term and robust supply to Europe; (2) Being integrated in EU with regulations and policies; (3) Most of the existing infrastructure already been paid off; And (4), a low environmental footprint compared to other providers. Being based on future hypothetical value chain scenarios, the study does not claim to give an exact picture for the future development in the Barents Sea, but rather highlight important elements, possibilities and key factors that can drive the development.

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1 Introduction

It has become evident that human activity causes global warming and that the main greenhouse gas (GHG) emitting sources can be linked to electricity generation, deforestation, agriculture and transportation, with the first and the latter being the fastest growing sources. There are still uncertainties regarding the nature and scale of the long-term effects of global warming but it has become clear that actions must be taken to avoid serious consequences. Climate change is of global importance since GHG have a global impact on the environment wherever they are emitted and actions therefore require international collaboration (Stern, 2006). The proceedings of the 2015 climate agreement in Paris established a new goal of limiting global warming to below two degrees Celsius, and to aim for only one-and-a-half degree above pre-industrial levels. The climate goal was set to represent the level of climate change that would prevent significant interference with the climate system while still ensuring sustainable food production and economic development in all participating countries. About two thirds of the available budget to maintain global warming has already been emitted into the atmosphere over the course of several decades, and current indications of increasing CO_2 emissions show that global emissions must start to decline rapidly if the two-degree target ever is to be reached. Therefore, the recent agreement aim for the globe to reach its peak of GHG emissions as soon as possible and to begin removal of the already emitted GHG no later than 2050 (Rogelj, et. al., 2016).

Considering the new global agreement, it may seem contradictory that the Norwegian government announced their 23rd and 24th licensing rounds, opening for increased petroleum activities on the Norwegian continental shelf (NCS), and especially in the north. Several blocks in the Barents Sea were included in the rounds, which is a sea area located far away from the actual consuming markets (Ministry of Petroleum and Energy, 2015, 2016). This has raised several questions regarding the transportation of the extracted hydrocarbons. Especially concerning the transport of natural gas to the European market. The only existing transport infrastructure for natural gas in the Barents Sea is the Statoil-operated liquefied natural gas (LNG) facility located on Melkøya in Hammerfest. Here, the gas is brought to shore through upstream pipelines before being liquefied and transported by specialised LNG vessels. Looking further south on the NCS there is a well-developed network of natural gas pipelines connecting the fields to processing- and receiving facilities located both domestically and abroad. The ongoing discussion surrounding Norwegian natural gas transport is how to ship the resources in the Barents Sea to Europe in the best possible way. The discussion also involves whether to increase the LNG capacity at Melkøya or to expand the existing pipeline network further north. The determining factors holding back the participants coming up with a solution is the actual resource base in the Barents Sea and whether the transport infrastructure or the discoveries should be in place first (Norwegian Petroleum Directorate, 2011; Gassco, 2012, 2014).

However, the climate concerns regarding the transportation of natural gas must be considered. For LNG, there is a lot of emissions linked to all its processes in terms of liquefaction, transportation, and regasification. The LNG facility at Melkøya requires a lot of energy and is powered by a gas plant and not the domestic electricity grid (Statoil, 2001). Pipelines in general does not emit large amounts of GHG but the compressors and auxiliary equipment pushing and pulling the natural gas through are mainly driven by dedicated turbines or electricity produced by smaller gas turbine plants, which are directly linked to most of the emissions in the petroleum industry (Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017). The emissions related to the extraction and production of oil and gas constitutes a significant share of the Norwegian total of emissions, but the actual use of the hydrocarbons extracted is mostly emitted elsewhere due to combustion of final products by end-consumers. However, the emissions connected to the petroleum activities domestically represents a significant share of GHG emissions and cannot be disregarded (Gavenas, Rosendahl & Skjerpen, 2015).

Gaseous emissions into the atmosphere is considered an unavoidable part of hydrocarbon-exploration, production and processing operations. The reported figures for the members of the International Association of Oil & Gas Producers (IOGP) show that about 280 million tons of CO_2 and 1,8 million tons of CH_4 was emitted in 2015. The amount of energy required to extract, produce, and transport the hydrocarbons is very high and most of this demand is met by gas driven turbines out on the fields. The numbers for 2015 showed that companies on average consumed 1,4 gigajoules of energy per ton hydrocarbon produced (IOGP, 2016). If natural gas is assumed to be the main source of energy it would be the equivalent of approximately 37,6 Sm^3 per ton produced.

The premise stating that, “the complete combustion of one molecule pure methane with two molecules of pure oxygen results in one molecule of carbon dioxide gas, two molecules of water vapour, and energy in the form of heat”, supports the promotion of natural gas as a more environmentally friendly alternative compared to the other fossil fuels. However, the issue is that natural gas rarely consists of pure methane (CH_4) and that the combustion takes place in air and not pure oxygen. This fact results in additional pollutants than the one molecule of carbon dioxide, such as carbon monoxide (CO) and nitrogen oxides (NO_x) (Mokhatab & Poe, 2012). The European Commission (2011) have stated that natural gas will play a key role in the transition to a low carbon society. Due to the lower carbon intensity, gas is favoured over coal and when the price on carbon emission increases, a switch from coal to gas in the power sector is predicted to occur. Imposing a price on the emissions to air is the common mitigating measure governments use to reduce their emissions. Carbon prices are included in the United Nations (UN) adoption of the Paris Agreement (2015), where they recognise its importance for providing incentives for more mitigating measures. Mitigating tools, such as carbon prices lead to more cost-efficient structures with the polluters covering the damages they inflict (Kaufman, Obeither, & Krause, 2016). As a consequence of increased carbon pricing, Energy Information Administration (EIA) (2016) expect that natural gas will offset the capacity drop in coal (and nuclear), thus keeping the demand of natural gas in Europe steady in the years to 2040.

1.1 Relevance

Already in 1995, Doré studied the Barents Sea geology together with its petroleum resources and commercial potential. Substantial reserves of natural gas could be proved in the Barents Sea, both on the Russian and Norwegian side. He concluded that the resources were sufficient but that economic exploitation of these was hindered by the low gas prices at the time, the distance to the market, challenging logistics, restricted drilling seasons and the overall environmental concern. In the case of Norway, he more specifically pointed towards the remoteness of the area, the climatic conditions and environmental precautions that had to be taken. Nonetheless, Doré predicted that by 2050 the Barents Sea would become a major centre for large scale oil and gas activities. In fact, the implications presented by Doré are the same challenges we are facing in the Barents Sea today, more than 20 years later.

The maturing of the NCS with the biggest discoveries already being developed has led to petroleum activities moving further north to look for additional resources. As of 25th April 2017, the Norwegian Petroleum Directorate (NPD) announced that the estimates of undiscovered oil and gas resources in the Barents Sea could almost be doubled compared to previous estimates. The Barents Sea is now expected to hold around 65% of the total undiscovered resources on the NCS. Being facilitated by the Norwegian government, new areas in the Barents Sea are opened for petroleum activities and licencing rounds are frequently being held to assign operators to the most promising blocks. However, the increasing activity in the northern areas does not come without challenges. At the Barents Sea Conference of 2017, the director of NPD presented the way forward for petroleum activities in the Barents Sea. Further mapping of the area will become crucial and an intensification of data acquisition will be important to clarify the actual resource potential. This foundation will need to be facilitated for the future Barents Sea to become a major oil- and gas province on the NCS. During 2017, a total of 15 exploration wells are planned which is a record in the area, and together with the field developments of Johan Castberg, Alta, Gohta and Wisting the activity is increasing. The statement: “If the companies are willing to collaborate to find good transport- and development solutions, the threshold would become much lower for development of new discoveries in the Barents Sea” (Nyland, 2017), further promote increased Barents Sea petroleum activities.

For natural gas to be evacuated from the Barents Sea, there is a need for additional transportation infrastructure. Even the well-developed pipeline network in the North- and Norwegian Sea there are no existing pipeline infrastructure connected to the Barents Sea. The northernmost pipeline connected to existing infrastructure that can be found on the shelf today is the Polarled pipeline connecting the Aasta Hansteen field to the Nyhamna processing facility. Developing connections from the Barents Sea to existing infrastructure will require heavy investments and the Norwegian transmission system operator (TSO) Gassco have called for collaboration among the industry participants. They further recommend to identify possible measures to bridge the gap between socioeconomic and project economic perspectives to be a focus area in near-term (Gassco, 2012, 2014). Transporting natural gas is an energy intensive operation, which provide the topic for this study. Natural gas from the Barents Sea will require transportation over long distances to reach its intended market, which also may be the reason for the development of the existing LNG facility rather than pipelines. Offshore operations together with processing facilities account for some of the largest single points of emissions in Norway, which will be of great importance for the development of new infrastructure in the Barents Sea. As of 2016, Gassco exported more than 108 billion Sm^3 natural gas through the pipeline network with an average energy consumption of 10,9 kWh per Sm^3. Accounting for the emissions from the Norwegian electricity mix of 27 gram CO_2 per kWh generated (Torvanger & Ericson, 2013), a rough estimate would give a unit emission intensity of 294,3 gram CO_2 per Sm^3 natural gas equivalent to 294,3 kg CO_2 per Sm^3oe. However, most of the energy in the petroleum industry cannot be based on the Norwegian electricity mix alone because of the long distances from shore and the widespread utilisation of gas turbines for power generation (Norwegian Petroleum Directorate, Petroleum Safety Authority, Water Resources and Energy Directorate, Pollution Control Authority, 2008). This fact means that the emissions per unit will be hard to determine on a general basis and that it may vary according to where the gas is extracted, where it is delivered, and how it gets there. With the Norwegian petroleum sector being subject to both domestic carbon taxation together with the European quota system, the emissions from producing, processing and transporting Barents Sea natural gas to the market will come at a cost (Norskpetroleum, 2017a). However, this cost is directly connected to how the value chains are configured, thus providing the development of new infrastructure the option of reducing these through energy efficient solutions. The emission cost related to petroleum activities in the Barents Sea will depend on the future price set on carbon emissions. The Intergovernmental Panel on Climate Change (IPCC) (2014a) have stated that a carbon price is an essential measure to keep global warming below 2 degrees and that the future will consist of strict carbon prices and favour energy efficient solutions. Large emission related costs might also lead to a shift in the energy markets, thus making potential infrastructure developments in the Barents Sea exposed for a market risk. Besides the questions surrounding the potential resource base, an ongoing debate is whether Europe’s gas demand will experience a drop when the impact of the Paris Agreement intensifies. For gas infrastructure to cover its investment it requires decades of profitable operations and demand. The market risk of reduced demand is therefore of high relevance for Barents Sea natural gas. Many environmentalists suggest that to maintain the two-degree target, all fossil fuels need to be kept in the reservoirs and that clean energy sources must balance the decline (News Deeply, 2016, October 25). This will have a significant impact on the petroleum activities on the NCS and on the overall European energy mix. However, the likelihood of this scenario materialising is rather uncertain and it is predicted that fossil fuels will hold the majority in the energy balance for several years to come. (Energy Information Administration, 2016)

1.2 Research Objectives

The overall aim of this research is to advance the understanding of the impact of carbon pricing policies on natural gas value chains, focusing on natural gas produced in the Norwegian Barents Sea. To investigate the impact, it is necessary to understand and identify the emissions present in Norwegian natural gas value chains and more specifically the emissions occurring when transporting the gas to Europe. The development of carbon pricing combined with its influence on Norwegian natural gas transport infrastructure has not been covered in the existing literature and therefore opens for a whole new area of research.

Therefore, the drivers and barriers behind carbon pricing policies and natural gas infrastructure development is of great importance to highlight the opportunities and possible obstacles in the case of Norwegian natural gas from the Barents Sea. This research will further assess the existing carbon pricing policies that already have or will have a future impact on the Norwegian natural gas supply. The nature of the topic made it beneficial to focus on emissions from the natural gas value chain and carbon pricing as two individual subjects. First, an in-depth review of relevant literature and empirical emission data were gathered to investigate potential Norwegian natural gas value chains from the Barents Sea to Europe. Followed by the second, focusing on the development of carbon pricing policies in Norway and the EU to investigate the impact on the different value chains and the competitiveness of Norwegian gas supply. A more detailed description of research strategy and data collection methods is provided in section **1.3 Structure**. Within the context of carbon pricing and emissions related to Barents Sea natural gas transport, the research objectives for the study have been set to:

1. ***Identify*** the CO_2 emissions from hypothetical constructed value chains transporting natural gas from the Barents Sea to the European market.

Here we will conduct carbon footprint analysis on hypothetically constructed value chains transporting natural gas from the Barents Sea to the European market. The analysis will consider the unit emission intensities for various value chain scenarios transporting natural gas from the Barents Sea to the European market, including both pipeline- and LNG chains

2. ***Explore*** the effects of carbon pricing on the identified emissions from the hypothetical value chain scenarios and investigate what an intensified carbon price will constitute regarding the cost of these.

Here we will use the identified results from the carbon footprint analysis and discuss the impact of carbon pricing and the effect of a carbon price corresponding to the two-degree target set by the Paris Agreement. This section will also link the identified carbon footprints together with theory of carbon pricing by putting a price on the emissions from the hypothetical value chain scenarios.

3. ***Address*** the competitive advantages for Norwegian gas supply and the impact of carbon pricing on the future Norwegian natural gas to Europe.

Here we will discuss the impact of carbon pricing policies on the future position of Norwegian gas supply to the European market. This discussion will be used to show how our research contributes to strengthen the Norwegian supply to Europe related to its competitive advantages.

The research objectives presented will serve as the research questions for the study and the aim is to answer them as best we can as we go along. The main findings and results will be presented in the last three chapters: **6. Carbon Footprint Analysis**, **7. Putting a Price on the Carbon Footprints**, and **8. Impacts on the Norwegian Gas Supply**.

1.3 Structure

This section will describe the structure of the thesis with respect to the necessary steps in solving the research objectives. Taking the context of the research into account, the thesis and investigation is structured into three main sections:

1. Carbon footprints from Norwegian natural gas value chains.
2. Putting a price on the emissions from the value chains.

3. Investigating the impact on the competitive advantages of Norwegian gas supply.

The first part is introduced to the thesis with the purpose of estimating the emission intensities from a set of hypothetical value chains that acts as scenarios for future Norwegian Barents Sea gas delivered to the European market. The value chain scenarios will be further described in the chapter of the carbon footprint analysis. The second and third part of the thesis is formed as a discussion of the carbon footprints obtained to address the impact of developing carbon pricing policies in Norway and Europe. The theoretical framework required to understand and grasp the underlying aspects of what is discussed through the thesis is very comprehensive and is linked to each of the three sections.

1.3.1 Data Sources

The study is based on a collection of secondary data gathered from academic, governmental and company publications and technical reports. The data used for estimating the emission intensities for the value chains included in the study is gathered from annual field specific reports submitted to the Norwegian Environmental Agency and the trade organisation Norwegian Oil and Gas Association. However, some of the data had to be extracted from impact assessments, plans for development and operations of a petroleum deposit (PDO´s) and plans for installations and operation of facilities for transport and utilisation of petroleum (PIO´s). The actual calculations of the carbon footprints are based on the framework established by Shaton's (2017) research. Data on carbon pricing, taxes and quotas, are gathered from Norwegian and EU documents, reports and other publications on the subject. The calculation of the cost of carbon pricing regiments will be based on the results obtained from the value chain emission intensities and the carbon pricing policies present in Norway and the EU. The discussion will be based on the gathered literature and theoretical review conducted in the framework of the thesis. To answer the problem formulation of the impacts on the Norwegian model of gas supply, several topics needed to be investigated. Especially with respect to the resource potential and infrastructure development in the Barents Sea and the demand for Norwegian natural gas in Europe. The research design has been developed to investigate the carbon footprint of natural gas value chains together with future Norwegian and EU carbon pricing policies. The aim is to uncover the actual cost of the emissions from Norwegian natural gas supply and how the development of petroleum activities in the Barents Sea can be impacted by these.

1.3.2 Approach to Research

The distinction between qualitative and quantitative research is framed by the terms of whether the research consist of words or numbers, together with the use of open-ended or closed-ended questions. A combination of these is known as mixed methods research which is an approach where both qualitative and quantitative data is collected and integrated into a distinct design. This research method has gained acceptance because of its ability to provide a more complete understanding of research problems than qualitative or quantitative methods alone (Creswell, 2014). The thesis is a mixed methods study that address the impact of carbon pricing policies on Norwegian natural gas value chains. A sequential mixed methods design is applied which is a design where first the quantitative data is gathered, treated and analysed before presenting the findings and results. Further the quantitative results are discussed in line with a comprehensive collection of qualitative data formed as a literature review and theoretical framework.

1.3.3 Research Design

A case study is a design in which the researchers develop an in-depth analysis of a case. The case is bounded by time and activity and detailed information is gathered using a variety of data collection procedures over a sustained time-period. ((Stake1995; Yin 2009, 2012), cited in Creswell, 2014)). Our case is concerned with Norwegian gas supply to Europe, and specifically natural gas from the Barents Sea together with the continuous development of carbon pricing policies and other mitigating measures being enforced on the industry participants. The design of the thesis takes the form of a case study with the overall aim of investigating the carbon footprint of natural gas transport from fields in the Barents Sea to the European market, and the impact of carbon pricing policies on the future position of Norwegian gas supply in a greener European environmental regime. The research design and work process can therefore be summarised by the following steps:

- Comprehensive in-depth literature search and establishment of the theoretical foundation.
- Construction of value chains for Barents Sea natural gas transportation.
- Gathering of reports on emissions from field and processing facilities.

- Creating an excel database for all emission data
- Calculating value chain carbon footprints using Shaton’s (2017) framework.
- Connecting the literature to the results of the carbon footprint analysis.
- Discussing the effect of carbon pricing policies on the carbon footprint from the value chains and their effect on future Norwegian natural gas supply to Europe.

1.3.4 Literature Reviews

Creswell (2014) defined the purpose of a literature review as a tool to help determine if a topic is worth studying and providing ways for how researchers can limit their scope to a specific area of research. A literature review serves several purposes: 1) Presenting results from other studies that are closely linked to the one being conducted. 2) Relating the specific study to larger ongoing discussions, identifying gaps in literature, and extending existing studies. And 3), indicating the importance of the study while acting as a benchmark for its results. In our thesis, the review of literature is separated and focused on two specific topics since the research is separated into carbon footprints of Norwegian value chains and the impact of carbon pricing policies on future Norwegian gas supply. The purpose of which our literature review serve is to help the reader understand what is to be investigated in the research and to show that existing research on the combination of these topics is extremely limited. However, it shows that the ongoing discussion related to emission mitigation measures, gas transport and climate policies has a lot of attention in the industry. The importance of our study is reflected through the lack of research on the area surrounding carbon footprints from Norwegian gas transport value chains and especially in the Barents Sea. It will also act as an extension of the research conducted by Shaton (2017) which only investigated the carbon footprints from existing value chains on the NCS.

1.3.5 Scenario Based Research

A scenario is defined by Kosow & Gaßner (2008) as a description of a possible future situation which includes the path of development that leads to that specific situation. The scenario will however not be used to give a complete description of the future but to highlight important elements of the possibilities and key factors that will drive the development. It is also stated that scenarios in fact are hypothetical structures and should not claim to fully represent reality. The hypothetical value chains that will be presented in this study can therefore be considered potential future scenarios for gas transport solutions for natural gas from the Barents Sea to the European. However, it is not likely that these value chains will be fully accurate nor resemble the actual future situation for the Barents Sea. Scenarios can also be used to test reliability, robustness, and effectiveness of policies (Kosow & Gaßner, 2008). Given our findings on emission intensities we can test the policies of carbon pricing with respect to the choice of pipeline or LNG technology for transportation of Barents Sea natural gas. By doing so, we can evaluate if current carbon pricing policies promote the most environmentally friendly alternative or if it experiences any shortcomings.

2 Natural Gas

The relevant aspects of natural gas will be presented through this chapter to give an understanding of its components and value chain characteristics. This will in turn provide the reader with the necessary knowledge to grasp the rest of the thesis.

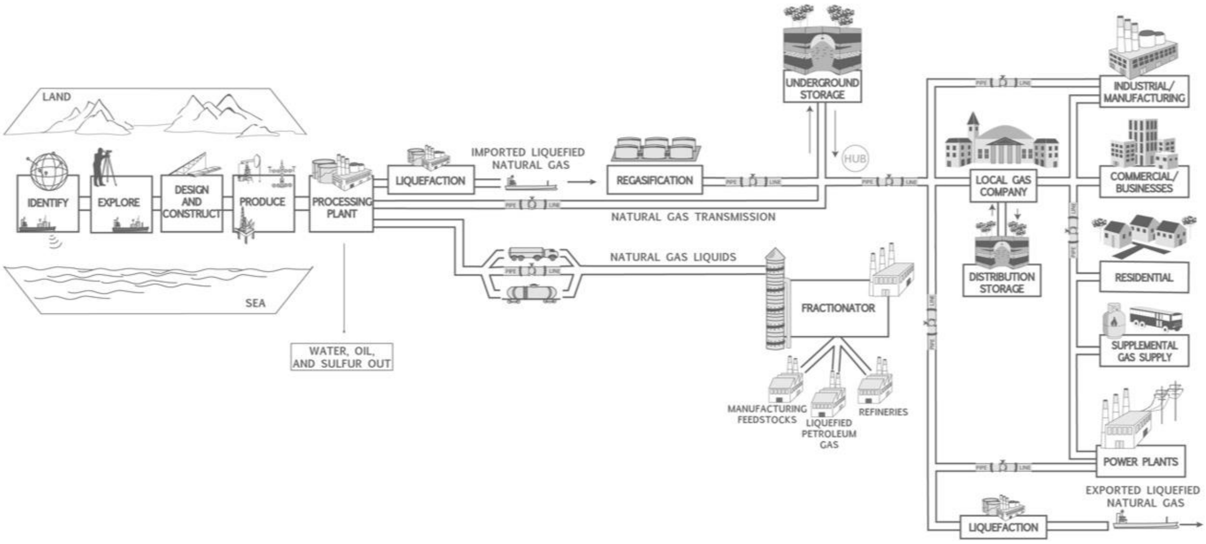
2.1 Natural Gas Value Chain

Among the fossil fuels, natural gas is the most energy efficient due to its energy saving benefits compared to oil and coal. Being used as fuel in power generation is its primary purpose, but it is also used in the residential sector, and as a source of hydrocarbon in petrochemical feedstocks and elemental sulphur for industrial chemicals. Natural gas consists of a mixture of hydrocarbon and non-hydrocarbon elements that acts as gas under atmospheric pressure. The gas can contain several hundreds of different compounds which can vary from one well to another, or even within the same reservoir. The primary ingredient in natural gas is methane (CH_4), but it can also contain larger quantities of ethane, propane, butane, and pentane. One can also find traces of hexane and heavier hydrocarbons. Usually, natural gas contains nitrogen, carbon dioxide, hydrogen sulphide as well as other sulphuric components. The natural gas can further be separated into different types depending on the proportion of hydrocarbons that are heavier than methane alone (Mokhatab & Poe, 2012).

Table 1 Natural gas types and components (Source: Gassco, 2017a).

	Rich gas	**Dry gas**	**LNG**	**Wet gas**	**LPG**	**Condensate**
Methane	■	░	▒			
Ethane	■	░	▒	■	░	
Propane	■			■	░	
Butanes	■			■	░	
Naphtha	■			■		
Condensate						▒

Understanding the value chain for natural gas is a comprehensive task as depicted in the figure below. The stages and length from discovery to end-use may vary significantly according to the chosen paths, as well as the correlating emissions along the various stages and processes. Therefore, this section will try to describe the natural gas operations relevant for this study which will highlight the processes of transporting natural gas by pipelines or as LNG.



Upstream → Midstream → Downstream

Figure 1 Natural gas value chain (Source: American Petroleum Institute, 2013).

The physical value chain for offshore natural gas can be divided into the business segments of upstream, midstream, and downstream. Upstream involves exploration and production of natural gas, while midstream is concerned with processing and transmission, and downstream which covers the refining and distribution of various final products. The participants in the value chain such as shippers and traders link the upstream and downstream business segments together by buying natural gas at the wellheads and selling to utilities and end-consumers (Weijermars, 2010). Tomasgard, Rømo, Fodstad, & Midthun (2007) provided a general step-wise presentation of the pipeline value chain for Norwegian natural gas:

2.1.1 Production

Natural gas is produced at offshore fields where gas is extracted from reservoirs beneath the seabed. Several wells penetrate the reservoirs and gas is gathered at the offshore installation or subsea facility. Gas can also be gathered from other adjacent reservoirs, so-called tie-ins, before being prepared transportation.

2.1.2 Transportation

The gas is further transported through pipelines driven by compressors, which push and pull the gas through the various stages of the value chain. Pipelines can be merged together and the pressure for all pipelines must therefore be greater at the entry points than the exit points for the gas to flow in the right direction. The current network on the NCS consist of 8.200 km (Gassco, 2017b) of different pipelines. Here, the gas from different fields and of different quality are mixed in the network to meet the desired specifications. There is also a distinction between pipelines used to transport gas to processing facilities and pipelines used to transport processed gas to the market. The first can be classified as pipelines used for upstream transportation while the latter is known as dry gas- or export pipelines.

2.1.3 Processing

Natural gas from the fields may contain various contaminants that must be removed before the gas can be sold with the right specifications. Therefore, processing facilities remove the contaminants in the rich gas such as ethane, propane, and butanes. The processing operation is normally performed at onshore facilities, but can also be done at offshore installations. The separated petroleum gases (LPG) are exported by designated vessels to separate commodity markets. After processing, the remaining dry natural gas, mainly consisting of methane and some ethane, enters the transmission system and is exported to receiving terminals in Europe.

2.1.4 Storage

Storage of natural gas may be required in periods faced with over-production or low demands, but is also utilised to cope with peak-demands. The various types of natural gas storages can consist of abandoned fields, aquifers and salt caverns. These storage alternatives are important since they provide flexibility to the value chain as they make it possible to store natural gas close to the market and to be utilized to cope with variations in demand. However, the Norwegian storage capacity for natural gas are very limited compared to the volumes exported.

2.1.5 Receiving Terminals

These are landing facilities for processed dry gas and the end-destination for the export pipelines. The gas is delivered to the terminals with pre-determined pressure levels and energy content which is specified by terms of delivery in contracts.

2.1.6 Distribution

Transmission lines from the receiving terminals to the buyers and end-users are part of the downstream transmission network. This part of the value chain is considered outside the scope of the Norwegian natural gas transportation system, which ends at the receiving terminals.

2.2 Liquefied Natural Gas

Natural gas in its liquid form is what we know as LNG. When cooled to temperatures below minus 160°C natural gas transforms from its gaseous form into its liquid state. LNG is a clear, transparent and odourless liquid that reduces the volume by a factor of approximately 600 compared to its gas-form. This reduction is what allows natural gas to efficiently be stored as LNG for multiple uses and to be transported by other means than pipelines alone such as LNG carriers. In 2015, the American Petroleum Institute published a guidance document for estimating greenhouse gas emissions from LNG operations. The methods aimed to estimate GHG emissions from all LNG operations and to consider the diversity of the operations. To understand the emissions from the LNG value chain it is necessary to investigate each operation and its contribution related to emissions. The value chain for LNG consist of five interconnected stages generally known as liquefaction, storage, loading and discharge, shipping, and regasification.

2.2.1 Liquefaction

Natural gas arrives directly from fields or in some cases from initial processing before entering liquefaction plants. Prior to liquefaction, contaminants such as water, sulphur, residual CO_2, and other components that may complicate the liquefaction process or be harmful to the facility must be removed. The process of liquefying natural gas consists of one or more LNG-trains that produce rich or lean LNG with respectively high or low heating values. Normally LNG is consisting of a minimum of 90% methane together with fractions of ethane, propane, and butanes. However, it is possible to obtain LNG consisting of 100% methane depending on the feed gas and the hydrocarbon recovery technology. The process of liquefying the feed gas consist of several treatments followed by cooling the gas until it reaches the desired temperature for it to be stored as LNG. The emissions present in the liquefaction process is usually a combination of fuel gas combustion to generate the required power for refrigeration and electricity, heaters, flares, incinerators and other heat generating processes, venting of carbon dioxide, fugitive losses of natural gas, and fugitive losses of other gases.

2.2.2 Storage

The main task for the storage operations is to store LNG at the liquefaction facilities prior to loading and at receiving terminals prior to regasification. However, storage tanks can also be utilised in distribution systems for peak-shaving when demand is fluctuating. The tanks are double-hulled like what is known in the shipping-industry but with the space between the walls being insulated to keep the LNG refrigerated.

2.2.3 Loading and Discharge

Loading and discharge operations are undertaken at the liquefaction facilities and the receiving regasification terminals to load and discharge the LNG carriers. Specially designed loading arms transfer LNG between vessels and terminals or facilities. The LNG is kept in its liquid form during operations and all loading racks and connectors are insulated to reduce generation of boil-off-gas (BOG) and as a safety measure throughout the operation. The loading arms are designed with a capacity that can vary between 4.000-6.000 Sm^3 LNG per hour and are usually installed in pairs or in threes. The emissions in the cargo handling operations are minimal because of the associated piping system is welded rather than flanged with low amounts of escaping gas.

2.2.4 Shipping

The LNG carriers transporting LNG from liquefaction facilities to receiving regasification terminals are double-hulled and insulated to ensure safe and reliable operations. The tanks are specially designed to maintain the temperature and pressure between minimum and maximum levels. BOG management systems are installed to manage vaporisation and safe use or disposal while in port and on voyage. Traditional LNG carriers use the BOG as fuel through installed steam turbines while supplemented by fuel oil or diesel to obtain the required propulsion power. New LNG carriers, normally larger tankers, are equipped with

re-liquefaction plants to liquefy the BOG and transfer it back into the tanks. Rather than running on the BOG, these carriers are slow-steaming with diesel-powered propulsion systems resulting in lower cargo losses during voyages. The containment systems installed on LNG carriers can be separated into spherical-, membrane- and structural prismatic designs. Nowadays, most newbuildings are delivered with the membrane design.
The GHG emission from LNG carriers will vary according to the specific design of their propulsion- and containment systems, capacities, and rate of utilisation. Emissions are generated along all stages of the shipping operation, while sailing, berthing and de-berthing from liquefaction facility- and receiving terminal docks, and loading and discharging LNG.

2.2.5 Regasification

The main operation at the receiving regasification terminals is to transfer the LNG back to its gaseous state. The regasification unit is typically located and incorporated at the actual receiving terminal. LNG is pumped from the storage tanks either for further transportation in liquid form, or pressurised and vaporised before being transported in its gaseous state trough pipelines. The composition of the LNG received may vary according to the treatment the natural gas experienced prior to and in the liquefaction process. Therefore, processing steps after regasification may be required to obtain correct specification before export. Additional processing steps within the regasification operation may contribute to increased GHG emissions. Traditionally, most of the emissions in this operation stage can be traced to combustion processes for compressor operations and power generation.

3 The Norwegian Continental Shelf

This chapter will present the current situation and development for natural gas on the Norwegian continental shelf together with its emissions and mitigating measures. It starts by addressing existing literature before going into the status on the shelf.

3.1 Literature Review

Aasness, Bye and Mysen (1996) explored the welfare-effects of emission taxes in Norway where they used a long-term general equilibrium model of the Norwegian economy. The model was run to generate scenarios to represent the differences of whether to implement a carbon tax or not. The objective was to investigate the relationship between gross domestic product (GDP) and the level of carbon taxation in Norway. In other words, how would an increased carbon tax on hydrocarbon production impact the Norwegian economy. The study showed that an increased carbon tax could increase the gross domestic income (GDI) even if GDP were reduced due to increased carbon taxation.

In 1999, the Centre for International Climate Research (CICERO) published a report on the development of emissions to air from the Norwegian petroleum industry while comparing it to the other domestic sectors. Potential mitigating measures with costs and effects were discussed to highlight the most promising, and the ones that led to reducing emissions at the lowest abatement costs. Results showed that power generation were the largest contributor to NO_x and CO_2, and that environmental agreements, taxes and quotas were favoured as mitigating measures to cope with emissions (Dragsund, Aunan, Godal, Haugom, & Holtsmark, 1999).

In 2001, a report on the environmental effects of Norwegian export of gas and gas power were presented. However, the report discussed the effects of increased gas production on the total of CO_2 emissions in Western-Europe and not the specific emissions related to the gas transport itself. The results however showed that increased production could contribute to lower emissions in the short-term, while long term effects were dependent on investments in other energy sources (Aune, Golombek, Kittelsen, & Rosendahl, 2001).

Bruvoll & Larsen (2004) analysed whether the implementation of the 1991 carbon tax resulted in a reduction of Norwegian emissions. The aim of the study was to reveal the driving forces behind the changes in CO_2, CH_4 and N_2O in the period of 1990-1999 and provided an empirical conclusion of whether price-based incentives such as carbon taxes worked as a policy tool. The study concluded that despite ambitious Norwegian climate regulations and policies, the carbon tax only had a modest influence on emissions. The authors explained the modest effect with the fact that the policy was not uniformly distributed throughout the Norwegian industrial sectors. Many energy intensive industries such as process industries, manufacturing, cement production, air and sea transport are partly or fully exempted from Norwegian carbon taxation.

In 2005, another CICERO report on climate policy instruments investigated various alternatives to be implemented in the Norwegian petroleum industry. Results showed that maintaining the CO_2 tax together with the incorporation of EU-ETS quotas would not contribute to significant emission-reductions on existing facilities in the petroleum sector, though it could have an impact on new facilities being developed. Replacing the CO_2 tax with the EU-ETS nor had any significant effects on reducing emissions, but large economic consequences for the Norwegian state with a loss of 500-600 million NOK per year (Eskeland, Kasa, & Kallbekken, 2005).

Aune & Holtsmark (2008) considered if Norway would profit from an international climate agreement with an introduction of a global carbon price. Modelling showed that the substitute-effect for natural gas (rather than coal) were stronger than the direct reduction in demand, resulting in a higher producer price and increased consumption of natural gas. Since the CO_2 emission intensity were lower for gas than coal, an increase in gas consumption would result in lower global emissions. However, replacing coal with natural gas would still generate significant emissions.

The future of Norwegian natural gas production was subject to the study of Søderbergh, Jakobsson, & Aleklett (2009). Their objective was to highlight the differences between projections made by the Norwegian government concerning future Norwegian gas supply and the actual volumes to be expected. The authors based their predictions and scenarios on mathematical models, using real-life parameters. The study modelled fields to generate production profiles, and undiscovered resources were included to make valid forecasts. Their conclusion showed that Norwegian gas supply would decline by 2030, with limited potential to increase at any later point in time. The authors also stated that this would have negative consequences for the European security of supply and would increase their relative dependency to other gas providers.

In 2010, Fæhn, Jacobsen, & Strøm published a study that accounted for the socioeconomic costs of the Norwegian governments Climate Report for 2020 (Klimakur 2020) with the goal of reducing total domestic emissions with at least 12 million tons CO_2 equivalents. Results from macroeconomic modelling showed that a common emission rate of about 1500 NOK per ton CO_2 equivalents would be required by 2020 to reach this goal. This would come at an estimated annual cost of five billion NOK when including EU-ETS obligations and the Kyoto Agreement.

The same year, a paper was presented on the re-development project of the Valhall field on the NCS which discussed the background for replacing its turbines with PFS (power-from-shore)-technology. The main factors for choosing PFS were summarised to cost reductions, improved operational efficiency, minimising emissions and improving HSE elements. Estimates showed an annual reduction of about 300.000 ton CO_2 and 250 tons of NO_x which also resulted in significant savings considering the Norwegian carbon tax imposed on the shelf (Westman, Gilje, & Hyttinen, 2010).

Lundberg & Kaski (2011) investigated the emissions from the Norwegian oil and gas industry and the possible reductions of utilising PFS-technology on offshore installations. The report also considered the challenges associated with the management regime and necessary measures to promote more PFS with the most relevant being: 1) Altering the Petroleum Act to require PFS from day one, allowing for more predictable planning for the mainland power grid and collaboration in important geographic areas. 2) Large field alterations and re-developments should be required to utilise PFS. 3) Increasing the Norwegian CO_2 tax rate. And 4), establishing a climate fund like the NO_x-Fund which could finance further electrification of existing fields. It was also stated that to avoid global warming exceeding the two-degree target, developed countries were required to reduce their emissions with as much as 40% leading up to 2020. In addition, mitigating measures had to be introduced in developing countries.

In 2013, a study was conducted on the climate policies in countries producing fossil fuel, in the case of Norway. The focus of the research tried to find the optimal combination of mitigation policies, with carbon leakage as a major factor. The calculation of costs and policy alternatives were based on Norwegian data. Results showed that a tax per ton domestic CO_2 emissions and a tax per barrel of domestic oil extracted would be the optimal policy. The authors indicated that to reduce global emissions for an oil producing country such as Norway, most mitigating measures should be enforced on the supply side. Meaning that one should try to reduce production. This showed that mitigation policies with the objective to reduce carbon emissions could affect third parties, such as the society. A price on carbon emissions would lead to shifts in the economy, and in the case of Norway impact the volume of hydrocarbons exported and in turn the social benefits of its activity (Fæhn, Hagem, Lindholt, Mæland, & Rosendahl, 2013).

In 2013, CICERO investigated if electrification of installations on the NCS would lead to reductions in CO_2 emissions. A comparison was made to see if a platform utilising PFS-technology led to lower emissions than if the platform were equipped with traditional turbine technology. Results showed that if PFS-technology based on the Nordic electricity mix (100 g CO_2 per kWh), the emissions would be reduced with up to 90% compared to turbines. Considering the Norwegian electricity mix alone (27 g CO_2 per kWh), the reductions could be even larger (Torvanger & Ericson, 2013).

In 2014, a SINTEF research paper studied energy efficient technologies contributing to lowering the CO_2 emissions at offshore installations, two of which located on the NCS. The study focused on better and more efficient utilisation of turbine technology on the installations by recovering waste heat from the turbines and from the compressor trains used for gas exports. Results showed a potential 22% reduction of emissions and a saving of about 17 million USD considering the Norwegian CO_2-tax rate and reduced fuel consumption (Mazzetti, Nekså, Walnum, & Hemmingsen, 2014).

Gavenas, Rosendahl, & Skjerpen (2015) investigated the driving forces behind the CO_2 emissions related to Norwegian oil and gas production. The input for their analysis were field specific data provided by the oil and gas industry and the Environment Agency, which covers all Norwegian oil and gas production. The study consisted of linking the field data for CO_2 emission with the field data concerning production levels, reservoir characteristics, and ocean depths of the different offshore fields. The objective of the research was to see if the level of emissions coincided with field characteristics, and to see whether the price of CO_2 and oil had any impact. Findings showed that as production from a field reaches its peak and start to decline, the emissions per produced unit of oil and gas increased remarkably. The emission intensity also escalated as the amount of oil in the field reservoirs increased. The authors stated that the average emissions for 2012 on the NCS was 55 kg CO_2 per ton oil equivalent. As for the sensitivity related to the price of CO_2 oil and, it was stated that a high oil price provides economic incentives to develop energy intensive fields, thus increasing CO_2 emissions. Concerning the effect of CO_2 prices, indications showed that it would impact the overall emission intensity on the NCS, while a lower CO_2 price provided less incentives to reduce the emissions which could be expected.

Heggedal & Rosendahl (2015) considered the effects of Norwegian climate actions on other countries´ emissions and international climate policies in a socioeconomic perspective. Results showed that the direct effects of reducing domestic emissions were limited and that it did not provide any significant incentives for other countries to reduce their own emissions. This showed that it was not enough for only a few countries to engage in mitigating measures for global warming to be reduced. In other words, the mitigating measures should be introduced on a global scale with international agreements.

Most of the existing literature related to the NCS is concerned with possible mitigation measures (technology and climate policies) and their effect on the level of emissions. Driving forces and socio economic costs of reducing the overall emissions have been touched upon by several researchers. However, it seems to be a limited amount of research covering entire Norwegian value chain emissions, from the wellhead to the market, and nothing concerning potential value chain emissions from the Barents Sea. Filling this gap will be the first objective of this research.

3.2 Status the Shelf

The overall goals for the Norwegian petroleum industry leading up towards 2030 has been set to maintain profitable and safe production on current levels. In 2020, CO_2 reducing measures have been planned to commence with the aim of a reduction corresponding to 2,5 million tons CO_2 equivalents per year leading up toward 2030. By 2050, the industry has an ambition to maintain its position as the most important value creator in Norway and to increase the average recovery rate from reservoirs to a minimum 60%. Simultaneously the industry wish to remain world leading in low CO_2 emissions with development of new technologies and solutions for further reductions (Norwegian Oil and Gas Association & Norsk Industri, 2016). All companies operating on the NCS must submit annual reports regarding their emissions embodied in the Norwegian Pollution Act and Environment Agency regulations. The operators must register all emissions from their activities on the NCS in detail each year which also include field specific emissions. The registered emissions include both planned emissions and accidental emissions from their activities. (Norwegian Oil and Gas Association, 2016). The data from 2015 showed that emissions of GHG from petroleum activities on the NCS amounted to a total of approximately 14,2 million ton CO_2 equivalents. The emissions consisted of 13,5 million tons CO_2 and the remaining share originating from the release of methane (CH_4). These emissions accounted for about a quarter of the total Norwegian emissions the same year. Most of the emissions in the petroleum industry is linked to the combustion of natural gas and diesel in turbines used for energy purposes for offshore installations and facilities not connected to mainland power grids (Norskpetroleum, 2017a).

The NCS cover more than two million square kilometres (2 039 951km^2), meaning that it is close to six-and-a-half times bigger than the total area of mainland Norway, Svalbard and Jan Mayen combined. The Norwegian petroleum activity began in the North Sea and has gradually moved further north in the search for more extractable hydrocarbons. From the beginning of the Norwegian petroleum production in 1971, a total of 102 fields on the NCS have been in production. By the end of 2016, 80 fields were producing, of which 62 fields in the North Sea, 16 in the Norwegian Sea and two in the Barents Sea. The production from the fields amounted to a total of 230,6 million Sm^{3}oe. This figure is approximately 13% lower than the peak-production that was registered in 2004. The NCS is characterised by several mature fields approaching the end of their lifecycle. However, new technology prolonging lifecycles and new fields coming on stream will contribute to maintain stable production volumes for the coming years (Norskpetroleum, 2017b).

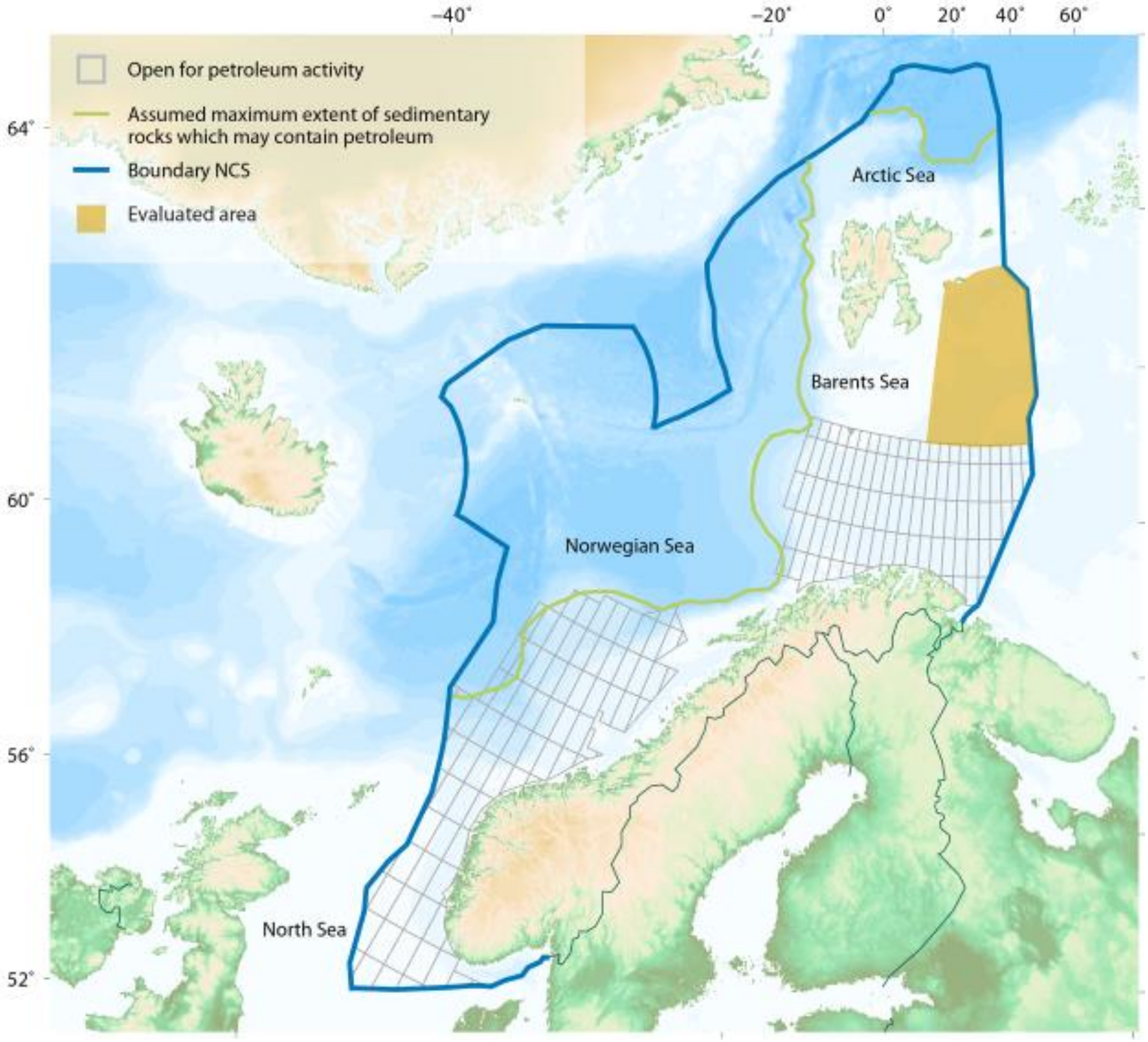


Figure 2 Map of the Norwegian continental shelf (Source: Norwegian Petroleum Directorate, 2017).

3.2.1 The Barents Sea

The Norwegian Barents Sea spreads across 772 000 km^2 and is the single largest sea area on the NCS. However, only the southern area of the Barents Sea (313 000 km^2) has been opened for petroleum activities and most of it is therefore still considered immature with little or no exploration. Nevertheless, the first discoveries in the Barents Sea was registered back in the 1980s and exploration have been going on for more than 30 years (Norskpetroleum, 2017c). In 2015, the 23rd licencing round was held by the Ministry of Petroleum and Energy (MPE) for petroleum activities on the NCS. The round consisted of 57 blocks, whereas 34 were in the all new South-East Barents Sea area and the remaining 20 in already opened areas. This came as great news for the operators as it was the first time since 1994 that the government had opened a new area on the shelf for petroleum activities. Already in 2016, the government invited the oil and gas companies to nominate new blocks for announcement in the 24th licencing round which is expected to be held before the summer of 2017. The aim of the government has been to promote exploration in a step-wise fashion in new and immature areas on the NCS to uncover more extractable hydrocarbons and adding to the existing resource base (Ministry of Petroleum and Energy, 2015, 2016).

In 2011, the NPD drafted four scenarios for the future petroleum activity in the Barents Sea. The use of scenarios allowed NPD to illustrate uncertainties by providing a range of possibilities through the different scenarios. The idea was to investigate the possibilities in each given scenario with different resource potentials. By examining the scenarios, it became possible to evaluate future decision-making and production for the NCS while focusing on:

- How long Norway will continue to be a significant provider of natural gas?
- Should new areas be opened for petroleum activities?
- When should the new areas be opened?
- How should existing infrastructure be utilised?
- Will there be a need for new infrastructure (pipelines, processing facilities)?
- Should development offshore or landing-solutions be facilitated?

The scenarios were formulated as to whether the resource potential was above or below expectations and if the discoveries were large or small, and if these were clustered or scattered. The time-horizon for all scenarios led up towards 2040. In 2012, the Norwegian transmission system operator (TSO) Gassco presented a study on the future gas transport infrastructure on the NCS. This was also developed with scenarios depending on different resource potentials. The scenarios were developed with means to establish transport solutions from offshore fields to the market while still maximising value creation from the Norwegian gas resources. The resource potential was only divided into a small, medium, and large a scenario. Already in 2014, Gassco published yet another report regarding the potential for new infrastructure development in the Barents Sea for gas transport. In the report, scenarios were based on existing fields and discoveries and prospects with drilling schedule from 2014 to 2017 together with NPD´s former projections of undiscovered resources in the area. Gassco developed five resource scenarios to cover the potential results of short-term exploration activity in the area. These scenarios consisted of high or low resource outcomes, and several small or a few large fields.

3.2.2 Field and Infrastructure Development

Licensing rounds with applications and awards are held be the Norwegian government on a regular basis for oil and gas companies to engage in petroleum activities within geographic areas on the NCS. Before the areas can be granted for licences the Norwegian Parliament must approve and open them for petroleum activities. This is a procedure that require impact assessments of the environmental, economic, and social effects of petroleum activities in that area, as well as its adjacent surroundings. After the decision of which blocks to include in a licencing round has been made, the oil and gas companies are invited to apply for production licences in the specified blocks. The MPE assign groups of companies based on the received applications and appoint one company the operator for the partnership of each licence. The operator is responsible for all the activities set by the terms of each specific licence, which may vary according to requirements set by the government. The strategic interest of participating in licencing rounds include factors such as securing access to additional resources, improving presence in certain areas, entering new areas, and to exploit existing infrastructure. When a new area is opened for petroleum activities, the environmental requirements and safe operations set by the MPE act as a benchmark. The mitigation of risks related to environment and safety are considered in the overall evaluation of the licence and is included as a cost element
(Hasle, Kjellén & Haugerud, 2009).

All infrastructure developments on the NCS face strict regulations. The Norwegian government imposes guidelines for infrastructure development and these guidelines relates to the PDOs and PIOs. The MPE in accordance with the Petroleum Act may approve a PDO and give special permits for the PIO compiled by the relevant actors. The plans conducted, forms the basis for the assessment and approval by the Government.
When infrastructure require connection to the mainland power grid, the Norwegian Water Resource and Energy Directorate (NVE), Statnett SF and local grid companies are all part of the planning process. The procedure from plan to operation include rules and regulations, and involvement from several organisations and authorities. These are laid down in the Petroleum Regulations, the Framework Regulations and the Temporary Regulations and involves the Norwegian Petroleum Directorate (NPD), the Petroleum

Safety Authority Norway (PSA) and the Ministry of Labour in the procedure. The Petroleum Act specify that the PDO must present a plan for the development of a petroleum deposit. This is conducted through two parts. The first part describes plan for production, while the second part is an impact assessment, highlighting the potential consequences of production. Operators holding the licensees where the relevant deposit is located prepare the PDO. The approval of a PIO will describe the plan for the installation and operation of a facility and constitutes an independent permit. The PIO usually also include the plans for transportation. Assessment of the potential impact related to the development/installation is an essential part of the PDOs and PIOs. According to the guidelines imposed by the Norwegian government, the impact assessment should 1) describe plans for field development and/or facility and the effects it can have on environment, natural resource and the society 2) discuss the significant positive or negative consequence that presumably could arise. 3) discuss remedial measures, as well as propose any necessary follow-up studies and monitoring programmes. The assessment should also have a separate chapter concerning environmental consequences and remedial measures, which highlight the potential discharges to sea and soil and emissions to air (Ministry of Petroleum and Energy, 2010).

3.2.3 Energy Production and Consumption

The emissions from Norwegian petroleum activities can mainly be traced to the combustion of natural gas in turbines used for power generation and direct operation of pumps, compressors and other auxiliary equipment. The emissions are also linked to diesel engines and flaring, but the contributions are not as significant. Being the major source of emissions, offshore power generation is a significant contributor to the value chain for natural gas. Offshore installations operating on the NCS can only receive their required power from three main sources, or a combination of these:

- Combustion of gas in turbines, engines or boilers.
- Combustion of diesel in turbines, engines or boilers.
- Power from shore (PFS).

The main factors affecting todays energy demand for energy in the Norwegian petroleum industry can be summarised as the following:

- Measures to improve recovery rates from mature fields, which contribute to increased energy needs for water- and gas injections.

- Transition from oil production to a larger share of gas production, which contribute to a substantial increase in energy demand for gas transport.
- Petroleum activities are moving further north, resulting in longer distance pipelines and increased energy demand to transport the gas to the market.
- Technological developments and discoveries on greater depths allow for more subsea operations, which in most cases also contributes to increased energy demand on the installations related to pumping, artificial lift, and heating. (Norwegian Petroleum Directorate, et. al., 2008).

Gas fields are very different to oil fields when it comes to lifecycles and energy consumption. There may also be significant differences from one field to another. The gas is normally extracted through natural pressure relief of the reservoirs which often is sufficient to transport the gas directly onshore or to other installations for processing. For the first part of their lifecycle the energy consumption will remain nearly constant if the reservoir pressures are sufficient. When the reservoir pressures start to drop, the energy demand increases to maintain sufficient pressure and transport the extracted gas to processing or through export pipelines. The pressure is maintained by compressors and auxiliary equipment. Gas field energy demands is dominated by the need for compression of gas related to extracting the gas and transporting it to and from processing, and is driven by the need to maintain pressures. Thus, gas fields energy demand increase along their lifecycles. An example from the Troll gas field showed that for the first ten years, production was sustained by a sufficient wellhead pressure that could transport gas onshore with a total energy requirement of only 2MW. After the first period, it would become necessary to install compressors to compensate for pressure reduction at the wellhead and power demand would gradually increase towards 160MW. In the case of the Troll gas field, the power is supplied from the Kollsnes processing facility, but fields without PFS will be dependent on turbine technology for this energy (Norwegian Petroleum Directorate, Oljeindustriens Landsforening (now Norwegian Oil and Gas Association), Statoil, Hydro, & ConocoPhillips, 2004).

In 1996, the parliament announced that prior to all new field developments, an overview of total energy consumption and the abatement costs of electrifying the installations had to be presented to give a comparison opposed to the utilisation of gas turbines (Ministry of Petroleum and Energy, 1996). In the aftermath of this announcement several reports were provided as measures to reduce the extent of gas turbines on the shelf. In 2004, the industry-participants on the NCS investigated the possibilities within power supply on offshore installations in the *“CO2 - Utredning av muligheter for mer effektiv energiforsyning på norsk sokkel”*. The report also presented a generic description of energy systems utilised offshore as well as the main drivers for consumption of the energy produced. The background of the study was to investigate possibilities that could result in lower emissions from offshore petroleum activities on the NCS. (Norwegian Petroleum Directorate, et. al., 2004). In 2007, the Norwegian Oil and Gas Association presented their report on different power alternatives to electrify the NCS titled *“Alternativ kraft til norsk sokkel”.* Replacing gas turbines offshore with clean hydropower from onshore electrical grids was considered as a measure to reduce CO_2 emissions on the shelf. In 2008, a study to update the findings related to electrification of the NCS was published by the relevant authorities in *“Kraft fra land til norsk sokkel”*. The report was aimed to estimate the abatement cost of electrifying the shelf related to the current CO_2 emissions from petroleum activities. However, only the equipment for power generation were replaced with clean energy from the mainland power grid (Norwegian Petroleum Directorate et. al., 2008).

Kesicki & Strachan (2011) explains marginal abatement cost as a policy tool used for indicating potential mitigating measures together with their associated abatement costs. Abatement cost is commonly used within environmental issues and it is increasingly being used within climate change policies. The term abatement cost can be explained as the cost for society to engage in measures to mitigate emissions, and in this context the cost of electrifying the NCS. The method for estimating the abatement costs of electrifying offshore installations rather than using turbine-technology was presented and updated in the Climate Report for 2020 (KlimaKur2020). The estimated abatement cost of electrifying the NCS ranged from 1.350-3.100 NOK per ton reduction of CO_2 emissions. These costs were based on electrifying certain areas on the shelf, divided into the southern-, middle, and northern North Sea, and the Norwegian Sea. The central factors influencing the abatement costs were the relationship between the price of sales gas and electricity price, lifecycle of the fields, and the preconditions for power supply. The cost of sufficient development of the onshore electrical grid were included in the costs. Also, included in the report were the abatement costs of supplying Melkøya LNG with power from the grid rather than the use of turbine technology. The cost of reducing emissions of about 300.000

ton CO_2 within 2020 was estimated to about 1.400 NOK per ton. An estimate of only replacing one turbine with electricity from the grid resulted in a reduction of 190.000 ton CO_2 by 2020 at a cost of about 700 NOK per ton. Similar estimations were also made for the Kårstø processing facility by replacing turbine-driven compressors and one generator, which could result in a reduction of 400.000 ton CO_2 at a cost of approximately 2.250 NOK per ton (Norwegian Environment Agency, 2010).

3.2.3.1 Power from Shore

It is the Norwegian Water Resources and Energy Directorate (NVE) that have the main responsibility for the energy system while Statnett is responsible for the national power grids. Most Norwegian electricity come from renewable hydro power with the exceptions of the gas power plants at Mongstad, Kårstø and Melkøya. In recent years, several renewable projects have been planned and applied for in Norway. Through utilisation of PFS-technology rather than turbines it is possible to reduce all turbine related emissions. In 2015, the Norwegian power generation of electricity amounted to a total of 144,5 TWh which is the equivalent of 144,5 billion kWh. Of which 95,8% was produced from hydropower, 2,5% from thermal power, and the remaining 1,7% from wind power. (Statistics Norway, 2016). Powering installations from shore with approximately emission free energy carriers such as renewables or gas power plants with CCS-technologies, all emissions connected to power generation offshore could be removed. A prerequisite is that the power used for electrification come from clean energy sources or sources where GHG emissions are captured and treated. Since 2008, several fields have been granted development or expansion without PFS-technology which could have avoided several thousand tons of emissions. Among the fields that have been developed without PFS after 2008 we find the Gudrun field, Valemon, Knarr and the expansion of Ekofisk and Eldfisk. Installations can either be fully or partly equipped with PFS-technology. When installations are partly electrified the turbines will only generate mechanical power and the ones generating electrical power replaced (Lundberg & Kaski, 2011).

3.2.3.2 Turbine Technology

A gas turbine works by the following principle: A compressor sucks air from its surroundings and compress it to increase pressure. The compressed air is then used in the combustion of gas in the combustion chamber. The warm pressurised combustion gases expand throughout the turbine and then transfers the energy onto a shaft or a drive. A share of the mechanical energy is used to run the turbine compressor while the rest is transferred to a generator or a compressor. The efficiency of a turbine is measured up towards 40% depending on its specification and size. Nearly two-hundred turbines are currently installed on the NCS with a total effect of about 3200MW. 81 turbines are connected to direct operations of mechanical equipment such as compressors while the remaining 101 is connected to electricity-producing generators. 86 of the turbines are single fuelled (gas or diesel) while 96 are dual fuelled (both). The actual efficiency of turbines installed on the NCS is estimated to be around 30% on average. Turbine efficiency shows how much of the heat energy in the fuel that is converted to electric power in the turbine (Norwegian Petroleum Directorate et. al., 2004). Since year 2000, all gas-fuelled turbines installed on the NCS has been equipped with dry low emission (DLE) technology. The downside with this turbine is that it requires much more space than the traditional single annular combustor (SAC) turbines and therefore leave less available space on the installations (Norwegian Petroleum Directorate, 2012).

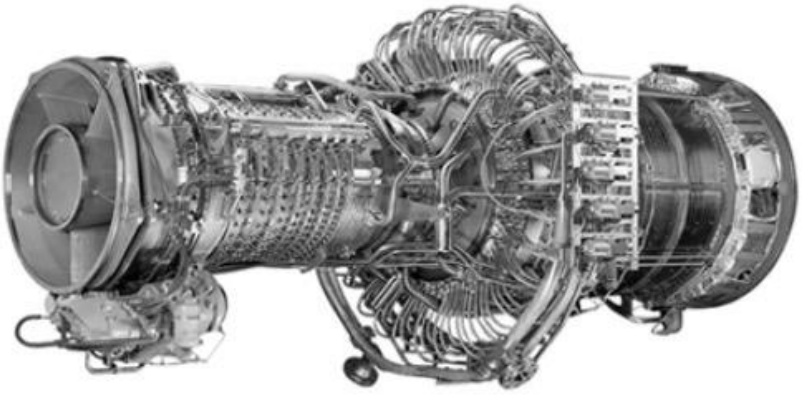


Figure 3 DLE turbine GE LM2500+DLE (Source: Norwegian Petroleum Directorate, 2012).

The cost of switching from SAC to DLE technology on the shelf has been estimated to lay between 50-200 or 350-600 million NOK depending on the turbines being adaptable or not. These costs have led to a limited degree of retrofitted turbines and thus there are still a lot of older SAC turbines in operation. In 2012, a total of 178 turbines were operating on the NCS whereas only 41 were equipped with DLE technology, which is regarded the best available technology (BAT) (Norwegian Petroleum Directorate, 2012).

3.2.4 Reporting of Emissions on the NCS

The Polluting Act enforce the operators on the NCS to comply according to the overall requirement for annual reporting in accordance with regulation §34 c. The guidelines have been developed as a measure to ensure consistent reporting from all operating licenses on the NCS. The establishment were done in compliance with the NEA, NPD, and industry participants. The aim of the reporting is to be transparent and to reflect the different fields development with respect to production, drilling, and correlating emissions. The NEA use the annual reports as a measure to control that the operators comply with the regulations on the shelf and to evaluate the development of the petroleum activity over longer time-periods. The operators are required to provide all data and figures to be included in the report no later than March 15th the following year and reports from all operators operating the different licenses on the shelf is gathered in one database. Several elements and data must to be submitted in the report but in the context of this study, only the overall description of the fields and facilities status and the emissions to air from combustion related processes will be included. The overall description of the reports is like fact sheets of the respective field or facility. Here, the operators must describe the installations and wells covered in the report as well as subsea-structures and tie-ins. It is required that changes to the installations compared to previous years are to be stated as well as the permits for emissions out on the field. The year of the PDO and start-up is to be included together with the expected schedule for the shutdown of operations. Transport solutions for oil, gas and condensate are also to be explained as well as where it is transported. Finally, the production with historical data and forecasts needs to be illustrated. The same applies for onshore facilities for processing and liquefaction. The second part is concerned with the emissions to air from combustion processes on fixed installations as well as mobile installations or vessels operating on the field. The emissions are to be distributed to the respective source of where they originate. The sources listed in the tables in the reports are; flaring, turbines (SAC and DLE), engines, boilers, well tests, well workovers, and others. In the same table the operators are obligated to specify the volume of liquid fuel and fuel gas combusted as well as the total amount of CO_2, NO_x VOC, CH_4 and SO_x emitted from the various sources (Norwegian Environment Agency, 2015).

4 Norwegian Gas Supply

This chapter will present relevant theory and literature regarding Norwegian natural gas supply, its level of performance in terms of emission intensity, and the demand. This will further be assessed to highlight its key features.

4.1 The Norwegian Gas Market

The export of Norwegian natural gas has its beginning in the 1970's. Negotiations concerning the sale of gas occurred, when discoveries of major gas deposits was made together with oil in the fields Ekofisk and Frigg. The operating companies that held the licenses of the areas made agreements with gas importers on the Continent and in the UK. The long-term contracts between exporter and importer or so-called depletion contracts was initiated, where the exporter dedicate all gas production from a certain field to the buyer. The contracts involved take-or-pay clauses, which made it possible for exporters to mitigate the risks involved in the downstream distribution of gas. Nevertheless, the established long-term depletion contracts were a pre-condition for further large investments in the upstream, midstream and downstream business segments (Austvik, 2003). The flow of gas through the Norpipe pipeline, which connected the Ekofisk field to Emden in Germany, marked the beginning of dry gas sale from the Norwegian continental shelf in late 1977. The following year, the Frigg Transport pipeline was developed and linked the NCS to St. Fergus in Scotland. In 1986, a shift in the supply of natural gas became evident. The discovery of the giant gas field Troll generated the need for a different contract structure. With no single buyer on the demand side that could commit itself to buy the giant volumes, together with a cost-intensive development of the field, it became required to generate a portfolio of sales to different buyers. Opposed to the conventional depletion contracts, the Troll contract was the first agreement that could be characterised as a supply contract, where the source of origin was less important than the volume delivered. The sale of gas from Troll was organised through The Gas Negotiating Committee (GFU), which performed commercial negotiations with purchasing stakeholders (Sunnevåg, 2000). In 2001, a significant reorganisation of the Norwegian natural gas sales occurred and was influenced by three determining factors:

1) Statoil had grown an interest for, and saw the benefits of being partly privatised. A proposal of selling 20% of the equity to private owners was sent to the Parliament in 2000. To avoid conflict of interests related to the privatisation, the Government proposed an

establishment of two new fully state-owned companies. The financial interests of the state were to be ensured through Petoro AS and Gassco, the latter which would serve as an independent and neutral transmission system operator (TSO) on the NCS.
2) The Norwegian Government recommended to abandon the GFU-system due to investigation made by EFTA Surveillance Authority. A concern of the current competition was addressed by EU and raised questions regarding its efficiency and legal considerations. And 3), the Norwegian government agreed to implement the "gas directive" from the EU into the Norwegian law. The gas directive's agenda was to ensure market efficiency by creating free movement of gas between producer and customer (Austvik, 2003).

As result of the reorganisation, the new TSO Gassco became operative on 1st of January 2002. The objective of the establishment was to ensure efficient allocation and utilisation of resources by non-discriminating behaviour towards all producers and buyers as well as playing an important role for infrastructure development. Gassco became a natural monopolists, which was convenient due to the large capital expenditures evident in the developing phase (sunk costs). Today, the government regulates access and tariffs for the use of transport capacity through the *"Regulations relating to the stipulation of tariffs etc. for certain facilities".* The relevant areas subject to the regulations is here specified, together with a detailed stipulation formula used to determine the cost per unit to use an entry- or exit point, or processing facility (Norskpetroleum, 2017d). To cover for the large investments cost with a reasonable return on the capital invested, the tariff is designed with a capital element, which decreases gradually year after year. For instance, the pipelines exporting dry and processed gas to Europe, such as Europipe, Zeepipe and Franpipe, have been operating for around 20 years, resulting in a low capital element. Infrastructure in which the capital expenditures have already been paid off will in turn provide lower tariffs and transportation costs (Gassco 2017c). Gassco work on the behalf of Gassled which is a joint venture of major actors that are the formal owners of the infrastructure on the NCS (Arentsen, 2003). Gassco operates today in the business through four parts: 1) Technical operations of existing infrastructure. 2) Infrastructure development. 3) Capacity administration. And 4), system operations (GASSCO 2017d). In 2016, they delivered 108,6 bcm to the European gas terminals, which was 99,71% of the volume ordered (Gassco, 2016).

4.1.1 The Emission Intensity on the NCS Compared to Other Regions

One of the key aspects which determines the Norwegian supply is its emission intensity in the production phase. Gavenas et. al., (2015) provided representative emission data for the petroleum activities on the NCS and the IOGP (International Association of Oil and Gas Producers) has since 1999, collected environmental data from its members, with the objective of clarifying status quo in the industry. IOGP's intensive collection of emission data provides an overview for the members regarding potential improvement areas. In 2015, 75 countries reported their emissions with a total of 280 million ton CO_2 emitted to air. The report show that most emissions is a result of combustion of fuels for production, flaring and the separation of CO_2 to meet sales specification. The latter activity usually vents the gas directly to air, if not CCS is integrated in processing operations. IOGP applies the term "emissions per unit of production" for comparing the different producers. In 2015, the average production performance from IOGP member countries resulted in 129 ton CO_2 per thousand-ton oil equivalent. The data gathered from the member countries only accounts for about 28% of the total global production, thus not providing a complete nor representative global indicator. The average European emission measure for 2015 were 91 ton per thousand-ton oe. production. 88% of Europe's production were reported, hence making it a better indicator for the European petroleum industry. Regions such as North America (210 ton CO_2 per 1000 ton produced), Africa (185 ton CO_2 per 1000 ton produced) and Asia/Australasia (170 ton CO_2 per 1000 ton produced), are all above the average IOGP emissions figures for 2015. The reported North American figures only cover 17 % of their production, which makes the indicator poor and unreliable. However, the report stated that data from the latter two, covering respectively 61% and 33% of total production reported, gives a broader performance indicator. The Middle-East region had the lowest reported amount of emission per unit produced. The average yielded 53 ton CO_2 per thousand-ton oe. produced. However, only 23 % of Middle-Eastern production was reported, thus giving a week indication of their actual performance (International Association Oil & Gas Producers, 2016). In 2013, the environmental footprint of different LNG value chains, from wellheads to receiving terminals were assessed by Glave & Moorhouse. The research investigated the emissions within the LNG industry and highlighted the best practices among the producers. GHG emissions from different value chains was modelled by using real-life data collected from the industry. The approach could provide inaccurate input due to non-neutral reporting, but gave a foundation for comparison. The authors indicated that the LNG facility at Melkøya together with the Snøhvit field had the cleanest LNG production in the world. Melkøya LNG could therefore act as a benchmark for the entire industry. The results obtained for Melkøya showed that for each ton LNG sold, the facility only emitted 0,35 ton GHG to air. This is marginally better than the second-best Gorgon plant in Australia, which emitted 0,36 ton. In comparison with the Sabine Pass LNG Terminal in the US., which produce LNG from both shale and conventional natural gas, the difference is much higher. The latter LNG facility emitted more than 1 ton GHG per ton LNG sold in a lifecycle perspective. The authors highlighted that it was a causality between shale gas production and high life cycle emissions. Three mitigation strategies were specified to mitigate CO_2 emissions from the LNG value chains: 1) CCS at the production stage. 2) Electrification of the processing facility. And 3), electrification of the liquefaction facility using renewable clean energy sources. Shaton (2017) referred to two determining factors for the cleaner production at Melkøya. Firstly, it benefits from a cold climate due and less energy is required for temperature regulations at the facility. Secondly, the use of CCS technology where CO_2 separated from the wellstream is reinjected back into underground formations under the Snøhvit reservoir. This shows that even if LNG operations can be very energy intensive, the Norwegian production is at the very forefront in a global perspective.

4.2 The European Demand of Norwegian Gas

As mentioned above, Europe have for several decades been the main consumer of Norwegian gas and provided Norway with sufficient demand, which have made it possible to develop an extensive pipeline network. The European gas market have been subject to governmental regulation through its entire history. In the beginning, monopolies were allowed, which led to vertically integrated companies, often state-owned companies that controlled parts of, and entire value chains. (Aune, 2008). The first initiative to directly liberalise the natural gas market, materialised through a working document of the Internal Energy Market, published by the EU Commission in 1988. They characterised the structure as an oligopolistic market where the control over gas transport distribution networks were held by private corporates or public-sector undertakings. The industrial organisation of the gas market led to an inefficient allocation of resources, thus leading to lower security of supply, expensive contracts and high transportation tariffs. The EU Commission specified that the obstacles preventing the desired level of competition in the market was governmental control of natural gas import and exports and undertakings holding a monopoly position (Andersen & Sitter, 2009). In the aftermath of the Commission’s statements, the EU proposed three guiding directives to create an internal natural gas market. The objectives of these directives were to introduce more competition and to liberalise the natural gas market to such an extent, that it lowered the commodity price and secured energy supply to Europe. The first two directives were concerned with the market transparency and the allowance of transit between transmissions pipelines. The last directive addressed the necessity for third party access (TPA) introduction and unbundling of the gas sales and transportation. A TPA introduction in the market involved allowances for third-parties to use transportation infrastructure, even if they did not own the infrastructure. The third directive indicated that direct contact between a suppliers and customers of natural gas was a requisite (free movement of gas), and that they should be given the right to negotiate transportation agreements. The third directive, or often called the “gas directive”, were set for implementation in 2000, after years of postponement (Austvik, 2003). As mentioned above, this had an effect on the gas transport structure in Norway. These directives have provided the basis for developing a liberal and liquid market with many exporting countries supplying Europe with affordable gas. Most the natural gas imported and consumed in Europe flows through a great pipeline networks from several large companies. Russian Federation ship the majority, supplying Europe with nearly 40% of their total pipeline import. Norway is the second largest supplier and shipped, in 2015, a total volume of 109,5 bcm gas. That is approximately 50 bcm less than the total amount exported from the Russian Federation. Netherlands accounts as well for a significantly large amount, with 40,6 bcm gas. The other transportation alternative to ship natural gas to Europe is as mentioned with LNG. Data from BP (2016) describe the LNG trade and total European imports for 2015. Naturally, much of the LNG trade are received from countries with well-developed LNG infrastructure and sufficient capacity. Qatar shipped 27,8 bcm natural gas to Europe in 2015, and is well above the second largest supplier Algeria, who provided Europe with 13,1 bcm. From Hammerfest at the LNG facility Melkøya in Norway, the total LNG volume sent to Europe were 3,1 bcm in 2015. The remaining amounts of the total 6 bcm were shipped to the rest of the world. Europe's natural gas consumption represents a large and important share of the energy mix and is primarily used for energy purposes as input source in thermal power stations, in manufacturing and or in the residential sector (European Union, 2016).

Even though Europe is well provided by many gas suppliers, the region is still concerned about the security of supply due to the risk of fluctuations. Since Europe is a major energy consumer, it is a vital concern among decision- and policy makers in EU to ensure safe and reliable supply of energy. The European Commission (2014) conducted an in-depth study regarding the security of energy supply. According to the authors, potential measures to mitigate this risk is to create reliable, transparent and interconnected energy markets. In the report by Belkin, Nichol & Woehrel (2013), they tried to identify potential energy diversification approaches to reduce the dependency of Russian gas. They addressed EU’s future dependency of Russian gas as vulnerable and further investigated potential sources of alternative supplies. A key element in EU’s energy supply strategy has been to increase and shift to a greater use of gas, and the predicted increase of gas consumption together with a decline in domestic production points towards a challenging situation concerning EU’s largest gas provider Russia, which has been subject to fluctuations in the past decades due to political disagreements. Russia has also yet to agree with EU’s competition and liberalisation strategy (the gas directive). The state-owned oil and gas company, Gazprom, which produce and control the majority of Russian natural gas export, are strongly against the liberalisation policy, since it would force Gazprom to sell its stakes in European distribution networks. EU finds it hard to achieve an independent energy policy, without the influence of the Gazprom, who behave monopolistic. The report from Belkin et. al., (2013) also specifies that other exporting regions, such as North Africa and Central Asia needs to improve its political system to export any extra volumes.

5 Carbon Pricing

This section will present the relevant literature and theory related to carbon pricing and policies, which will be further discussed. The aim of this theoretical framework is to provide the foundation for examining the research in the thesis.

5.1 Literature Review

The literature review is chronologically structured and separated in two parts. First part presents relevant international emission and climate studies. The objective is to see whether any international climate studies, have touched upon our field of research. The second part presents relevant scientific articles, which study the actual effects of climate policies. The aim is to uncover whether competitive advantages can be obtained in markets of strict environmental regulations.

5.1.1 International emission- and climate studies

Jaramillo, Griffin & Matthews (2007) compared the life cycle emissions to air from coal, natural gas, LNG and synthetic natural gas used for electricity generation in the US. The emissions were measured in CO_2 equivalents, SO_x and NO_x and showed that natural gas was more environmentally friendly than the other sources combusted in existing power plants, with LNG as the second-best fuel source in its best case.

Sumner, Bird, & Dobos (2011) assessed the existing US and international carbon tax policies together with their design and effectiveness. Considerations where given as to which sectors to include in the policy, the tax rate level, allocating the revenues, the impact on the consumers, and finally how to ensure a reduction of emissions.

Stephenson, Doukas, & Shaw (2012) critically assessed the promotion of natural gas as a transition fuel into a low carbon society. The authors stated that the life-cycle emissions of shale gas and LNG were too high to be considered a bridge fuel and could result in over-investment in carbon intensive developments. One could argue that since the study only consider shale gas and LNG in the US., it is not representative for Norwegian supply and Europe. However, it is important due to the topic it represents with respect to the low carbon society.

Bradbury, Clement, & Down (2015) investigated the GHG emissions and fuel use within the natural gas system using a Sankey diagram methodology. They defined the natural gas system as production, transmission and storage, processing, distribution, and end-use consumption. The authors found a split where approximately 20% of the CO_2 emissions in the natural gas system could be attributed to upstream and midstream operations while the remaining 80% could be traced to end-use. Their results showed that CO_2 emissions upstream and midstream mainly could be traced to combustion of natural gas for compression, flaring, and processing.

5.1.2 Climate policies impact on competitiveness

The traditional view on environmental regulations, entail an ecology versus economy situation, with compromises between the social benefits and the private costs imposed on the industry. Porter & Linde (1995) argued that the generic view on environmental regulations was wrong. In the real world dynamic competition is the building block of the economy and not subject to a fixed demand, technology and processes, as economic theory suggests. Porter´s hypothesis say that a well-designed regulation can trigger innovations and new technology, which increase efficiency. Implementation of an environmental regulation may therefore provide incentives for optimal utilisation of resources and improvements of production processes, thus offsetting the environmental cost. The authors indicated that improved productivity through regulations would generate more competitive advantages rather than less. The authors further highlighted that global demand is on the path of valuing low-pollution and energy-efficient products. A conclusion could be drawn that success promote innovation-based solutions that represents both environmentalism together with industrial competitiveness.

Baranzi, Goldemberg & Speck (2000) made a survey of future of carbon taxes and their effect on competitiveness and the environment. Although this study was conducted many years ago, it provides insight of the traditional consensus regarding environmental regulations. The authors conclude that competitiveness was not weakened in cases where mitigation policies were implemented.

The potential competitive advantages in a world of increasing environmental concerns was assessed by Lash & Wellington (2007). The aim of the study was to educate industries regarding the potential risks and opportunities present in a time of increased attention to global warming. The authors recommended a four-step process to improve competitiveness: Quantify carbon footprints, assess the carbon-related risks and opportunities, adapt their business, and to do it better than their rivals.

Haszeldine (2009) presented a report on the possible reductions of CO_2 emitted from coal- and gas power plants by introducing CCS technologies. Findings revealed that simply putting a price on carbon were not enough to incentivise CCS-technologies and that it would require additional policies enforcing CCS operations. Results also showed that for coal or gas combustion to become more sustainable, a rapid development of industrial scale CCS operations had to be commenced. Also, being the single most effective direct climate action available to reduce emissions from power plants it was stressed that actions were initialised and investments increased.

Porter (2011) defined competitive advantage for a country to be its industries capacities to innovate and upgrade. Advantages could be gained by coping with pressure and challenges faced in the respective markets. Porter also states that competitive advantages was the attributes allowing a country or organisation to outperform its competitors, and by adapting an activity to environmental regulations their green competitiveness would increase (Scientific American, 1991).

Ambec, Cohen, Elgie & Lanoie (2011) provided an overview and highlighted the scientific findings up to 2011 concerning Porter´s hypothesis. In their concluding remarks, it becomes evident that environmental regulations incentivise innovation among industries, thus making the theory valid.

The paper by Costantini & Mazzanti (2012) elaborate whether Porter’s statement that environmental regulations results in technology innovation and competitive advantages. The aim of the study was to explore the impact on EU’s competitiveness by increasing environmental regulations. The authors conclude that mitigation policies foster green exports and would not undermine EU´s competitiveness, hence proving Porters theory to some extent. Increased efficiency balance the imposed cost of the mitigation policies.

Zakeri, Dehghanian, Fahimnia, & Sarkis (2015) linked environmental regulations and supply chain planning practices using optimisation models. The study used an Australian based company for data and scenarios, and investigated carbon pricing versus emissions trading (quotas), in a supply chain perspective. The authors concluded that a carbon trading mechanism would result in better supply chain performance in terms of emissions, costs and service levels than carbon taxes alone. It was also pointed out that the field of green supply chain planning and climate change policies is increasing.

There have been conducted limited research concerning the effects of a carbon price corresponding to the two-degree target on climate efficient hydrocarbon-producing countries like Norway. Filling this gap will be a part of the scientific contribution of this paper and consist of assessing the potential competitive advantages for Norway, which might occur with and intensification of carbon pricing. The two-degree target was officially set in 2015 and signed in 2016. Research concerning any given effects has therefore not been provided yet. The current carbon price has yet to be increased in the aftermath of the Paris agreement, thus making credible conclusions hard to determine. However, as the literature review indicate, there have been conducted sufficient research concerning greenhouse gas emissions, green competitiveness, mitigation policies, and effects of similar policy implementations.

5.2 Climate Change is Market Failure

Stern (2006) referred to climate change as the greatest market failure that the world had ever seen. The social and financial cost of climate change can prove to be severe and have a large negative impact on global development. Standard economic theory discusses the fundamentals of externalities, market failure and its effect on society (Besanko & Braeutigam, 2010).

5.2.1 Market Failure

Climate change is a result of the externality associated with GHG emissions. The activity of emission intensive industries imposes a future cost due to the CO_2 and other emissions released into the atmosphere. The cost of this externality falls upon the society and is predicted to have severe consequences for future generations. These features make human-induced climate change an accurate example of a negative externality. Climate change leads to vital challenges for economics, due to the entailed cost that the unrelated third party experience or will experience in the future. When an economic activity impacts an unrelated third party, either positive or negative, it is referred to as an externality.

Browning and Zupan (2006) stated that externalities exist in markets where costs or benefits is not accurately reflected in the price of the product or service because of a firm's behaviour. In other words, the imposed cost of the economic activity is not fully covered or compensated by the emitter. Negative externalities are often associated with impacts to the environment such as water, soil, or air pollution. The global climate is considered a public good which was defined by Samuelson (1954) as; "*…a collective consumption good which all enjoy in common in the sense that each individual's consumption of such good leads to no subtraction from any other individual's consumption of that good…"* The benefit (and cost) of the climate can be enjoyed by an individual without diminishing the capacity of other individuals, or excluding others. Characteristics such as non-excludability and non-rivalry is key features for public goods. In the absence of public policies, there are little economic incentives for private investors to provide the right type and quantity of a public good. Thus, climate change can be viewed as an example of market failure involving externalities and public goods. There are some features that distinguish climate change with other externalities. 1) The climate change has global consequences and pollution have the same impact on the environment wherever it is emitted. 2) The impact of climate change is long-term and persistent. After GHG is released into the atmosphere, they will remain there for hundreds of years. 3) Climate change is associated with a high level of uncertainty and risks. In combinations with a long time-horizon the impacts are hard to predict in terms of magnitude, type and timing. And 4), the outcome of climate change will have severe impacts on the global economy if actions are not taken (Stern, 2007).

In a competitive market, where market failure is evident due to negative externalities which are not covered, there is a gap between the marginal social cost curve (MSC) and the marginal private cost curve (MPC). The cost of the externality will not be included in the private cost curve, while the social cost curve will include both the negative externality and private cost curve (Boardman, 2011). As an example, two scenarios can be investigated to illustrate the market failure associated with externalities. In scenario one, Firm X does not cover and compensate for the negative externalities that its activity generates. The market supply curve will be the same as the marginal private cost curve of firm X. The graph below gives an overview of the challenges that arises when negative externalities are not covered.

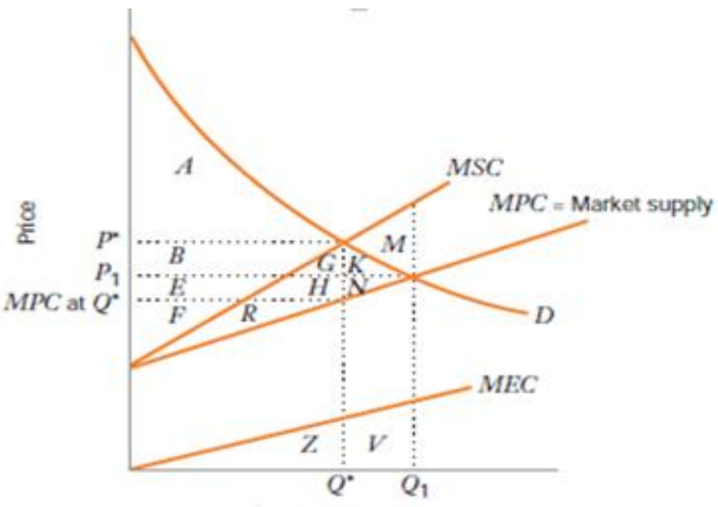


Figure 4 Graph illustrating externality and market failure (Source: Besanko & Braeutigam, 2010).

Price and quantity are represented on the axes, and MSC and MPC show the different cost curves, where MPC equals the market supply curve. The marginal external cost of the negative externality is illustrated through the curve MEC. This curve show the difference between MSC and MPC. The down sloping curve D, represent the demand curve of a market. The equilibrium will be where curve D intersects the cost curve MPC, which will give price P1 and quantity Q1 in this scenario. This generates a consumer surplus of area A + B + G + K. The producer surplus is the combined area of E + H + N + F + R, while the cost of the externality corresponds to the area in-between MSC and MPC, R + H + G + N + K + M. The second scenario highlights the shift that occurs when the negative externality is accounted for by the supplier. The market supply curve will equal MSC, while the demand curve is steady. The equilibrium will be at the point where MSC cross the demand curve D. This yields the social optimal price of P^* and a quantity of Q^* .
The consumer surplus is reduced to the area A, while the producer surplus equals area B + G + E + H + F + R. The cost of the externality is represented by the area R + H + G. The net social benefit is defined by adding consumer surplus and producer surplus and subtracting the cost of externality. In this case, scenario one will generate a net social benefit corresponding to area A + B + E + F - M. In comparison, the second scenario will result in a net social benefit of are A + B + E + F. In other words, a scenario where the negative externality is not accounted for nor covered by the supplier, a deadweight loss will occur, which leads to decreased net social benefit for society (Besanko & Braeutigam,

2010). Table 5 gives an overview of the economics explained above and highlights the loss of net social benefit that occur when negative externalities are not accounted for.

Table 2 Net social benefit of scenarios, both excluding and including the total cost of the externality (Besanko & Braeutigam, 2010).

	Scenario I	**Scenario II**
Consumer surplus	A, B, G, K	A
Producer surplus	E, H, N, F, R	B, G, H, E, F, R
Cost of externality	R, H, G, N, K, M	R, H, G
Net social benefit	A + B + E + F - M	A + B + E + F
Deadweight loss	M	

5.2.2 Correction of Market Failure

In the standard theory of externalities there are four methods to intervene and correct market failure: 1) Emitters cover the social cost of emission through taxes. For instance, with a carbon price that reflects the damage caused by the emissions. 2) Establishing restrictions to control the quantity emitted. 3) Property rights allocated among those causing the externality and those affected. For instance, a quota system that underpins trading among countries. And 4), establishing a single organisation to bring together the ones that cause and the ones affected by the externality (Stern, 2007).

5.2.3 Carbon Pricing as a Measure to Correct Market Failure

Carbon pricing is a collective term for putting a price or value on the emissions of GHG. The Kyoto Protocol originally defined seven GHG that was considered harmful to the environment in the long-term perspective, with CO_2 being the most important. The impacts from other gases are usually converted into CO_2-equivalents, to compare them on an equal basis. The objective of carbon pricing is to cover the negative externality that occurs when economic activities emit CO_2 into the atmosphere, and is a measure to restrict and correct market failure. Carbon pricing are usually a representative payable price or cost imposed on the emitter. Governments can intervene by putting a price on carbon emissions in two ways. The first alternative is to put a carbon taxation directly on the emitter. The cost is a product of the amount emitted, often calculated as a cost per ton CO_2 released to air. The second alternative is to be a part of a carbon market, which operates with carbon quotas. The price is set in the market and work on a cap-and-trade basis. In the quota market, there are a certain number of quotas, and the total amount works as a cap for all actors in the market. The actors are obliged to deliver a quota per ton of CO_2 emitted to the government. Since the quotas are subject to trade and can be exchanged among the emitters within the cap, an equilibrium price for the quota will occur. The price will represent the cost of emitting one ton CO_2. Activities that is energy intensive can buy quotas from less energy intensive activities, thus giving companies incentives to reduce their emissions. With the assumption that the carbon tax is equal for everyone, the quota system covers all emissions without any market power among the actors. Both mitigation mechanisms provide a more cost-efficient structure. For the companies, all mitigation measures that have lower costs than the relevant tax or quota price will pay off, thus leading to a reduction of emissions and more focus on other mitigating measures (Volden, 2013; Ministry of Finance, 2012).

5.2.4 A Mechanism to Change Market Behaviour

By implementing a carbon price, carbon-intensive sources of energy will increase its marginal cost relative to the cost of emitting carbon. In the case of natural gas, which emits about half the amount of CO_2 compared to coal, the related carbon price will have different impact on the two commodities´ marginal costs. Natural gas and coal serve as inputs in power plants, and in competitive markets the marginal cost of the individual power plants will determine a potential switch of fuel by favouring the less carbon intensive alternative. Carbon prices can therefore prove to be an efficient tool to reduce the use of the most emitting energy sources in power generation (International Energy Agency, 2016).

5.2.5 Carbon Leakage

For carbon pricing to perform in an optimal manner, a prerequisite is a non-discriminative price level among the emitters. Due to the global and integrated world economy, domestic mitigation measures such as carbon price implementation may lead to increased emissions somewhere else. This is referred to as carbon leakage. A global perspective is therefore of great importance when designing mitigation policies. The effects of carbon leakage can be divided into two categories. The first is the energy-market-effect. For instance, a potential mitigation policy among a group of countries may manage to reduce the consumption of conventional energy sources (oil, gas and coal), this will lead to lower commodity prices internationally and thus giving countries without that mitigation policy an incentive to increase their consumption. The second is the competitive-effect. Mitigation policies among countries may lead to increased production costs in the energy intensive sectors, like the petroleum industry. The profit for countries without the policy will increase, due to the loss of competitiveness for industries impacted by the mitigation policy. The scope of carbon leakage can be expressed by the following equation:

$$Carbon\ leakage\ (\%) = \frac{Change\ in\ emission\ in\ the\ rest\ of\ the\ world\ (ton)}{Reduced\ emission\ of\ countries\ implementing\ mitigation\ policies\ (ton)}$$

Macro analysis indicate that carbon leakage can amount to 10-30% if a uniform carbon price is implemented on large geographical areas, such as the EU. In smaller cases, for instance Scandinavia, carbon leakage is estimated to amount to as much as 60-90% (Bye & Rosendahl, 2012; Ministry of Finance, 2012).

5.2.6 In Socio-economic and Financial Analysis

Carbon prices are included when investigating potential investments and feasibility analysis. There are different ways to account for carbon pricing in these depending on the characteristics of the analysis. Financial analysis conducted by corporations apply a carbon price equal to the actual costs the actors are facing. For instance, the current or most likely carbon price levels. Socio-economic analysis internalises the externality and use carbon prices which reflects the “real” value approximations of the emissions. However, socio-economic analysis may also use the current carbon price if it represents the actual cost it inflicts on the society. Externality valuation in socio-economic analysis have two main approaches in terms of carbon pricing. The first is a carbon price equal to the marginal cost of damage. Although coming up with such a price that is correct has proven to be very difficult. There are methodological and ethical challenges with putting a price on carbon emissions equal to the marginal cost of damage, and poorer nations with low willingness to pay suffer the most. A price of carbon that correspond to the marginal cost of damage is referred to as a Pigou Tax. This price level gives an optimal socio-economic solution when pricing the emissions. The other approach is known as implicit valuation, where calculations are based on the carbon price governments could accept in line with binding mitigation targets. With the climate being a public good and climate change having an impact on a global scale, these targets should be of great importance worldwide.

Geographical origin of the GHG emissions, impose the same harmful effects to the global climate and environment. This implies that a global mitigation measure is the most ideal solution. For instance, a global uniform carbon price equal to the marginal cost of damage. Today, the alternatives that the standard theory of externality mentioned are evident. Taxation, restrictions, quota systems and organisation, such as the United Nations Framework Convention on Climate Change (UNFCCC), are all mechanisms to control and limit harmful emissions of GHG (Volden, 2013; Ministry of Finance, 2015).

5.2.7 Future Carbon Price Estimates

The International Centre for Climate Governance (ICCG) collected several valid studies concerning future carbon prices corresponding to the two-degree target. All studies used different modelling approaches which in turn generated different results. In NOU 2012:16 (Ministry of Finance, 2012), an average calculation of these data was conducted. The average carbon prices resulted 43 euro per ton CO_2 in 2020, 68 euro per ton CO_2 in 2030 and 235 euro per ton CO_2 in 2050 (all prices with monetary value of year 2012). NOU 2015:15 (The Ministry of Finance, 2015) used a UN report which suggested a median price equal to about 42 euro per ton CO_2 in 2020 to account for the two-degree target. The basis for the estimate was that the price had to be uniform and that all countries would contribute. In the Norwegian Climate Report “KlimaKur 2020”, (Norwegian Environmental Agency, 2010) it was estimated that a price per ton of carbon of 100 euro by 2030 would correspond with the two-degree target. The externality of GHG emissions can through these carbon price estimates be internalised in socio-economic and financial analysis. The European Commission (2011) projected a cost per ton of CO_2 between 100-370 euro by 2050. The cost was said to be consistent with obtaining a low carbon society. IEA´s world energy outlook (2014) projected a new policy scenario with a carbon price of 30 USD per ton CO_2 by 2025 and 50 USD per ton CO_2 in between 2030 and 2040. All the different figures above illustrate the difficulty of coming up with a single carbon price that fully cover the externality of climate change and emissions.

5.3 EU Climate Policies

UNFCCC – Setting the Agenda

The emergence of climate policies became a result of the growing consensus of the science on climate change highlighted by the inter-governmental negotiations in the UNFCCC. In correspondence with the negotiations, a binding commitment among all industrialised countries to mitigate GHG emissions to a level equivalent to 1990-levels were drafted. Despite little enthusiasm by the US and several other countries, the commitment was adopted and signed in 1992. This provided the framework for all the upcoming climate policy developments in the EU (Oberthür, Pallemaerts, & Kelly, 2010).

> *"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provision of the Convention, stabilisation of greenhouse gas concentrations in the atmosphere at level that would prevent dangerous anthropogenic interference with the climate system."* (United Nations, 1992)

Kyoto Protocol - Policy Formulation and Adoption

Even though the agenda on climate change was established, little contributions and mitigations strategies was implemented by the member states to stabilise GHG emissions. The aim of the Kyoto Protocol was to set more specific goals and in 1995 the negotiations began. EU proposed to aim for reductions CO_2, CH_4 and N_2O. The proposal was to be met by a "burden-sharing"-reasoning where all countries had to contribute, making the Kyoto Protocol an enhancement of the UNFCCC. The most important policy measure that materialised from the negotiations was the Emissions Trading Scheme Directive (EU ETS) in 2003, which further was linked to the international carbon market in 2005. This was the first multi-national cap-and-trade programme to be introduced and its coverage has increased ever since (Oberthür et. al., 2010).

The Energy and Climate Package – Evaluation of Adopted Climate Policies

In the following years, it became necessary to assess the current mitigation policies and prepare for the commitment period post 2012, as the Kyoto protocol first commitment period expired in 2012. In 2007, the European Council proposed the package known as the *"20-20-20 by 2020"*, which entailed a 20% reduction of GHG emissions, a 20% increase in renewables and a saving of 20% on projected energy consumption. The finalised package came in 2008 known as the *"Climate and Energy Package"*. In the initiative of designing policies the domestic EU climate policies went from being takers to becoming makers of international climate policies, and the EU became a vanguard for developing and implementing climate policies (Oberthür et. al., 2010).

The Paris Agreement

Already in 1996, the EU Council stated that their overall goal was to limit the increase of global average temperatures to two-degrees above pre-industrial levels. This statement has ever since steered the mitigations policies in the EU. A landmark agreement was reached in Paris in 2015. All parties in the UNFCCC agreed upon to undertake ambitious efforts to intensify mitigation measures and to make nations more robust to the effects of climate change. The aim of the agreement was to strengthen the global response to the threat of climate change. The objective of the Paris Climate Change Agreement was to ensure that global warming was limited to the two-degree target, while aiming to keep the temperature-rise below one-and-a-half degree. The parties agreed that this would reduce the impacts of climate change (United Nations, 2016a). Long-term climate planning became essential to achieve the objectives. The agreement established binding commitments for the countries to prepare, communicate and preserve a nationally determined contribution and to pursue individual national measures to achieve them. These national measures were to be reported every five years and the level of ambition should be increasing for each period submitted. In the short term, the Paris agreements act as a bridge from the current situation today towards future climate neutrality (United Nations, 2016b).

5.3.1 Climate Policies in Norway

It has been a long tradition in Norway for the government to apply economic incentives to reduce domestic GHG emissions. Today, as much as 80% of Norwegian emissions are subject to Norwegian CO_2 taxation and the EU-ETS, or both. Some industries have been exempted from the quota scheme, for instance agriculture, fisheries and most of the transport sector. Sectors such as domestic shipping and offshore vessels are also omitted by the CO_2 tax on GHG emissions. The magnitude and level of Norwegian mitigation policies are very high in an international perspective. In the Official Norwegian Report (NOU) 2015:15 it is referred to UN’s statement that: “the combination of the comprehensive coverage of sectors and the considerable level of taxations in Norway is unique in the world”, to highlight the strict environmental regulations. In a global perspective, only 10-15% of the emissions are covered by carbon taxes or quota schemes. With the petroleum activities on the NCS being subject to both CO_2 taxation and the European emissions Trading System (EU-ETS), the price per ton carbon emitted are equal to the sum of the carbon tax rate and the quota price. The Norwegian Government introduced the CO_2-tax on emissions in Norwegian territories in 1991. The law on taxation later included emissions from the petroleum industry on the NCS which initiated the beginning of several governmental regulations concerning GHG emissions from petroleum activities on the shelf (Ministry of Finance, 2015).

The table below show previous and current carbon taxation rates from year 2000 to today. The tax levels were stable in the period from 2000-2008, but the financial crisis of 2008 together with the implementation of EU-ETS for oil and gas companies contributed to a significant decline. From 2013 and up until today, the NCS have faced the highest taxation on CO_2 compared to historical figures.

Table 3 Historical CO2-tax level on the NCS (Ministry of Finance, 2016).

Year	**NOK pr. Sm3 of gas burned**	**NOK pr. Sm3 of gas released to air**	**Adjusted for inflation (2016)**
2007	0,8	0,8	0,98
2008	0,45	0,45	0,53
2009	0,46	0,46	0,53
2010	0,47	0,47	0,53
2011	0,48	0,48	0,53
2012	0,49	0,49	0,54
2013	0,96	0,96	1,04
2014	0,98	0,98	1,04
2015	1	1	1,04
2016	1,02	1,02	1,02
2017	1,04	7,16	1,03 / 7,06

The CO_2 tax rate for petroleum activities on the NCS in 2017 amounted to 1,04 NOK per Sm^3. This is the equivalent of about 445 NOK per ton CO_2 emitted to air when natural gas is combusted. For the emissions of natural gas released to air, the taxation rate amounts to 7,16 NOK per Sm^3. These two taxes were not distinguished in terms of prices until 2016 and both were priced at 1,02 NOK per Sm^3. The growing focus on the environmental damages caused by CH_4 alone led to the new increased taxation of released natural gas (Ministry of Finance, 2016). The GHG Emission Trading Act came into force in Norway in 2005, and in 2008 the oil and gas production were included in the trading system. This linked Norway to the EU-ETS quota system for GHG emissions. The introduction meant that the Norwegian petroleum industry had to follow the same emission trading scheme as other industries in the EU. About 50% of the Norwegian emissions are covered by the EU-ETS today and the trading scheme has put an upper limit of total domestic emissions. The Ministry of Petroleum and Energy (2017) estimated the sum of the carbon tax and the quota system for companies on the NCS which faced a total cost of CO_2 emissions of about 500 NOK. This cost is much higher than for any other sectors in Norway and very high compared to the price of emissions in other countries.

5.3.1.1 The Quota System – EU-ETS

The contributions from EU has historically been vital to reduce global warming, with their continuous implementations of ambitious policies. One of EU's cornerstones in reducing GHG emissions is the establishment of the EU-ETS in 2005. As mentioned, this system is based on a carbon cap level set to contain the amount of emissions within EU. EU designed a carbon market and imposed a financial value on the carbon savings, which act as a cost-effective incentive scheme, by entrusting the market forces to find the cheapest and most optimal way to reduce carbon emissions. Due to the need to cover their GHG emissions financially, continuous economic incentives are imposed on the emitter. Large polluting activities can be justified by buying credits from emission saving projects, for instance in developing countries around the world. In that way, the EU-ETS also contribute to low carbon technologies and solutions internationally. Currently, the EU-ETS is implemented in 28 EU countries together with Iceland, Liechtenstein and Norway. The system covers approximately 45% of the emissions emitted in the EU and impose restrictions on around 11 000 energy intensive facilities in power generation and manufacturing industry sectors. For the relevant industries not covered by the quota system will be fined of each excess tonnage of GHG emissions. This fine was set to 100 EURO/tCO_2 in 2013. Until now, the mitigation targets yield 20% reduction in the emissions to 2020 and 40% reduction towards 2030, compared to 1990 levels. (European Commission, 2016a) The quota price on carbon in EU-ETS was by the end of 2015 between 8,39 and 8,95 EURO. In 2016, the average CO_2-price in the EU scheme was estimated to roughly 5,3 EURO. In the short term, the quota price on carbon is determined by economic growth and energy usages. The price level on oil, gas and coal will also impact the level of the quota price. The prices on these energy commodities correlates with the quota price on carbon. The domestic policies and initiatives for more efficient use of less polluting energy is viewed as the key factor for reaching the goal set by the Paris agreement. As much as 80% of the GHG emissions in the EU are linked to energy production and consumption. This makes this sector a natural place to intensify mitigation policies (European Commission, 2016b).

6 Carbon Footprint Analysis

This chapter will be used to present the analysis estimating the carbon footprint for the hypothetical value chains transporting natural gas from the Barents Sea the European market. The focus of the analysis has been on the comparison of emissions from several value chains, including both pipeline- and LNG chains. The comparison has been made to come up with the unit emission intensities for natural gas produced and transported to come up with the total carbon footprints.

First the methodology for the carbon footprint analysis will be introduced. Here the actual calculations and initial assumptions will be described in detail. Then, a description of the hypothetical value chain scenarios included in the analysis will be presented together with the emitting sources present in each chain. These will be presented in the order of where along the value chain they are emitted. Finally, the results will be presented to illustrate and compare the carbon footprints for the value chains included in the analysis, accounting for configuration, power supply and distances. Further these figures will be used to investigate the effect of carbon pricing on the value chain emissions and to evaluate the future position of Norwegian gas supply.

6.1 Methodology

The background for which the analysis has been included in the research has been to establish the unit emission intensities for Norwegian natural gas supply from the Barents Sea region. Knowing the unit emissions makes it possible to show the cost and impact of carbon pricing. The analysis accounts for offshore field operations and production, upstream transportation, processing and export transportation. For the LNG chain, the operations of liquefaction and shipping is added to get a comparison against the pipeline chains. The resulting output is given as the emission intensity for the hypothetical value chains in kg CO_2 per Sm^3oe. natural gas produced and transported, from the wellhead to the market (1 Sm^3oe. natural gas = 1.000 Sm^3 natural gas).

To answer the overall problem formulation for the research and figure out how carbon pricing can affect future natural gas and infrastructure on the NCS we had to investigate the actual emissions related to future natural gas supply and its required infrastructure. Existing value chains for the transportation of natural gas, either by pipeline or LNG, acted as the technical foundation for estimation of the carbon footprints. Before conducting the analysis, we had to set scenarios with specific parameters based on data and reports published by the operators on the NCS and the TSO (Gassco). There are several published reports for the future of Norwegian gas transport infrastructure on the shelf and we therefore found it beneficial to apply similar scenarios and configurations for the value chains included (Norwegian Petroleum Directorate, 2011; Gassco, 2012, 2014).

The analysis had to account for various resource estimates in the Barents Sea since this is an immature area on the NCS with a lot of uncertainty connected to the volumes of hydrocarbons to be discovered. Furthermore, the transportation alternatives introduced also create a discussion whether to develop pipeline- or LNG chains. Another important issue was related to the power supply for processing facilities and offshore installations. The question was whether these stages in the chains would get their required power from shore using turbines or electricity grids, or if offshore turbine-technology would have to be applied out on the fields. Reviewing recent impact assessments, PDO´s and PIO´s provided the necessary information to come up with these assumptions. As a result, the value chains scenarios included consist of both PFS-technology and turbines, and combinations of these.

By investigating the studies on resource estimates published by Gassco and NPD it was assumed that the resource potential in the Barents Sea would be sufficient for investments in new infrastructure for pipeline transportation. This would mean to develop and connect pipelines to existing NCS infrastructure. Reports regarding additional resource potential in the Barents Sea, to the already existing 200 billion Sm^3, showed that the predictions were well above the volumes required for infrastructure development. Since only two fields currently have been developed in the Barents Sea, it was necessary to look further south on the shelf to find existing developments to represent potential new fields, pipelines and processing facilities. Since it is expected to be discovered more gas than oil in the Barents Sea the focus was primarily on gas fields with little or no associated oil resources. To be able to come up with reasonable results within the timeframe of the research, the number of potential fields had to be narrowed down. Therefore, the fields included in the analysis consist of “duplicates” of Aasta Hansteen, Åsgard, Norne, Ormen Lange and the existing Barents Sea gas field Snøhvit.

The value chains included in the analysis can further be separated into three categories. The first, Category 1 includes new discoveries in the Barents Sea that only will be connected to the existing pipeline infrastructure of Polarled, Åsgard Transport or the Norne gas transport system. The second, Category 2 includes new discoveries that will promote a new processing facility in the northern county of Nordland before a new pipeline will transport the processed gas to the Sleipner field for further transportation. The third, Category 3 include the already existing LNG chain in the Barents Sea that will act as a benchmark for comparing the carbon footprints from the different value chains in the analysis. The final destinations for all the value chain scenarios included is Easington in the UK, Dornum in Germany and Zeebrugge in Belgium.

The pipeline chains have been configured by the following reasoning: First, a discovery is made in the Barents Sea equivalent to either one of the fields already mentioned. The gas is further transported to either existing pipeline infrastructure for further transport or a new onshore processing facility located somewhere in Nordland with the same specifications as either Nyhamna or Kårstø. A new Barents Sea pipeline is developed to either transport rich gas to the existing pipelines or to transport the dry gas from the new processing facility to existing infrastructure further south on the shelf. When the gas has reached existing infrastructure, it will follow the existing transport infrastructure to its respective processing facilities for further treatment before being exported to its destinations in the UK, Germany or Belgium. The LNG value chain included will be the existing chain consisting of the Snøhvit field where gas is transported to Melkøya for initial processing and liquefaction before being shipped by LNG carriers to the hypothetical destination of Zeebrugge. This shipping route from Melkøya does not exist but is included to get a comparison against the pipeline chains over similar distances.

A fact sheet of production volumes and emission reports from fields and processing facilities was compiled to provide the data input for the carbon footprint analysis. This can be found in the **Appendix** which provide tables for all fields and processing facilities with their respective emissions and production and processing volumes for 2015. By applying the formula presented in Shaton´s (2017) framework, we obtain our results regarding the emission intensity for the hypothetical value chain scenarios. First the emissions from the fields had to be estimated and were obtained using the following formula:

$$UE^{Gas} = \frac{TE^{flaring} + TE^{boiler} + TE^{engine} + TE^{other} + r * TE^{turbine}}{\sum_{i=1}^{n}(V_i^{Gas} + V_i^{Oil} + V_i^{NGL} + V_i^{Condensate})} + \frac{(1-r)TE^{turbine}}{\sum_{i=1}^{n} V_i^{Gas}}$$

Table 4 Notation for unit emission formula.

UE^{Gas}	Unit emissions of CO_2
$TE^{flaring}$	CO_2 emissions of flaring
TE^{boiler}	CO_2 emissions of boilers
TE^{engine}	CO_2 emissions of engines
TE^{other}	CO_2 emissions of other sources
$TE^{turbine}$	CO_2 emissions of turbines
V_i^{Gas}	Volume of gas produced
V_i^{Oil}	Volume of oil produced
V_i^{NGL}	Volume of natural gas liquids produced
$V_i^{Condensate}$	Volume of condensate produced
r	The amount of energy used for other purposes than gas export compression

The data used as input in the analysis were gathered from the Norwegian Oil and Gas Association using the annual fields specific reports submitted for 2015 with emissions and production volumes. This fact contributes to a stronger and more reliable analysis rather than solely relying on theoretical parameters as shown in (Balcombe et. al., 2017). However, it was difficult to separate the specific emissions related to field operations and gas export compression, known as the “splits”, and this is the reasoning behind the use of *r* in the formula. Shaton (2017) allocated the various hydrocarbons according to their contribution on the total emissions. With turbines being the main source of energy for offshore fields without connections to the mainland power grid, the split was made to separate emissions into two parts. The first part of the emissions was allocated to the energy requirements for general operations on the installations such as water- and gas injection, pressure maintenance, electricity for living quarters etc., known in the analysis as field operations. The second part of the emissions was allocated to the operation of gas export compression for pipeline transportation. With little or no available data on how to distribute the energy requirements between the operations, an assumption was made such that 40% of turbine related emissions were allocated to the overall field operations on the installations while the remaining 60% was allocated to transport operations.

A challenge with estimating the emission intensity from the processing facilities came because of the submitted emission reports only presented figures for total emissions and did not allocate them in terms of the specific product that were processed or separated. To calculate the emission intensity from processing facilities a modest alteration of the formula had to be made. To get the unit emissions from each processing facility we divided the total emissions from all sources present on the total volume processed at each facility to get the unit emission intensity per Sm^{3}oe. processed. For the processing facilities with field dedicated processing operations such as Melkøya and Nyhamna, this was not an issue. But for Kårstø which process natural gas from several fields the total emissions had to be divided on all processed gas from all fields with the following formula:

$$UE^{Gas} = \frac{TE^{all\ sources}}{\sum_{i=1}^{n}(V_i^{Gas} + V_i^{Oil} + V_i^{NGL} + V_i^{Condensate})}$$

However, the same issue arises with allocating the amount of energy required for gas export compression as there are no specified split between the processing operations and export operations. Therefore, it is assumed with respect to emissions that processing and export compression is a combined operation in the cases where it cannot be extracted from the annual emission reports, PDO or PIO, impact assessment or other technical documents.

The output, or results, from the carbon footprint analysis show the unit emission intensity related to all stages for the pipeline chains and include the field, upstream transportation, the new Barents Sea pipeline, the new processing facility the connection to existing infrastructure, existing processing facility, and finally the export transportation to the market. However, it is difficult to separate these for all the chains due to factors such as fields being powered from shore and upstream and export transportation being included in processing facilities. The total emissions distributed among the stages may not be fully coherent with the real-life figures but provides a description of what is driving emissions.

6.2 Scenarios

The scenarios included in the analysis are based on existing fields, processing facilities and pipelines on the NCS. The map of the Norwegian gas transport infrastructure below will provide an overview that will better the understanding of the paths for the different value chains that will be explained and described through this section.

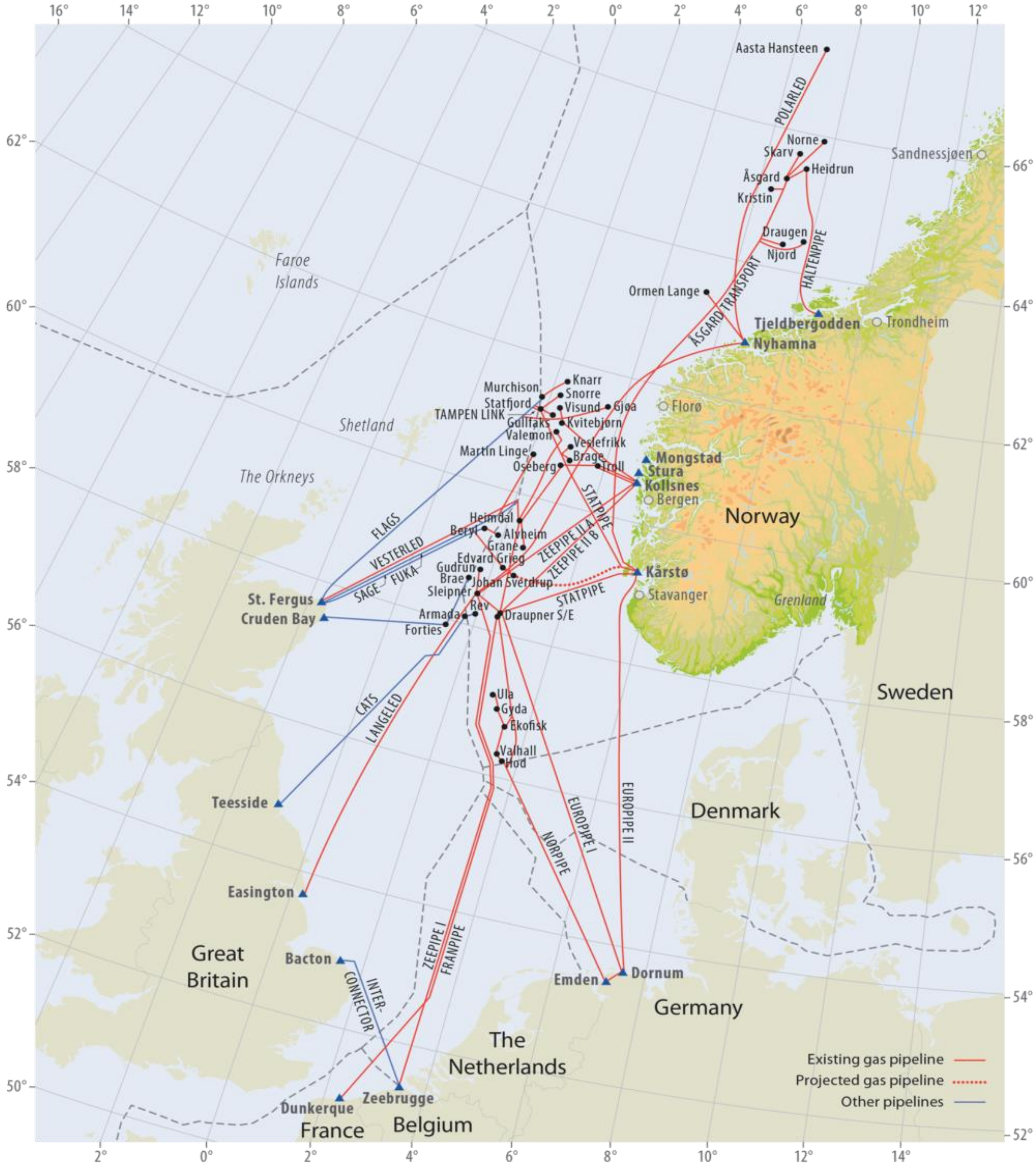


Figure 5 Natural gas pipelines on the NCS (Source: Norskpetroleum, 2017e).

Halbouty (2003) defined gas fields containing more than three trillion cubic feet, equivalent to 84 billion Sm^3, recoverable gas resources as giant gas fields. In 2009, Söderbergh et. al., further defined the fields containing more than 15 billion Sm^3 as semi-giant gas fields. For simplicity and the likelihood that the value chain scenarios will be developed for Barents Sea natural gas, we have only included giant and semi-giant gas fields in the value chain scenarios.

6.2.1 Category 1: Pipeline chains without new processing facility

There are three value chains included in this category to investigate the carbon footprint of new discoveries in the Barents Sea which connects directly to existing infrastructure through rich gas or multiphase pipelines before being sent to the European market.

Table 5 Category 1 value chain description.

Field	**New Barents Sea pipeline**	**Existing pipeline**	**Processing**	**Export pipeline**
1. Aasta Hansteen	1.000 km Polarled 36" pipeline	481 km Polarled 36" pipeline	Nyhamna processing facility	Langeled 42"/44" 1.170 km Easington UK
2. Åsgard	1.000 km Åsgard Transport 42" pipeline	707 km Åsgard Transport 42" pipeline	Kårstø processing facility	Europipe II 42" 658 km Dornum GER
3. Norne	1.000 km Norne gas transport system 16" pipeline	707 km Åsgard Transport 42" pipeline		

1. Aasta Hansteen – Easington

Operation	Unit emission intensity
Field	16,557
New Barents Sea pipeline	52,632
Existing pipeline	25,316
Processing	1,775
Export pipeline	0,000
Carbon footprint	**96,281**

A new discovery equivalent to the Aasta Hansteen field is in this scenario assumed to be discovered in the Barents Sea. The impact assessment for the field show that it is to be developed and powered by turbine technology with an estimated annual emission of 218.000 ton CO_2. Distributing these emissions to the fields annual expected volumes of hydrocarbons to be extracted (100.000 Sm^3oe. of condensate and 5.166.667 Sm^3oe. of gas) we come up with an emission intensity for the field operations equivalent to 16,557 kg CO_2 per Sm^3oe. Here we had to account for the share of emissions that could be linked to the field operations and used the 40/60 split.

The Barents Sea Pipeline in this case is an extension of the Polarled pipeline. To come up with the figures for emissions we had to use the obtained emission for Polarled together with the pipeline length of 481 km and multiply these to get the emissions for the new Barents Sea pipeline. Resulting in an emission intensity of 52,632 kg CO_2 per Sm^3oe. transported through the 1.000 km pipeline with a diameter of 36". Taking the impact assessment for Polarled into account, the capacity of the pipeline is estimated to be 58-70 million Sm^3 per day depending on where along the pipeline new connections are tied in. The existing pipeline in this scenario is the already established Polarled pipeline with an emission intensity of 22,316 kg CO_2 per Sm^3oe. The 481-km pipeline receive gas from the existing Aasta Hansteen field, the Kristin gas export project, and is also facilitated to accommodate new connections before transporting the gas to Nyhamna in Møre and Romsdal for processing

The processing facility at Nyhamna is powered by the mainland electricity grid in which energy source is renewable hydropower. Keeping in mind the Norwegian electricity mix of only 27 grams of CO_2 per kWh, the emissions from the facility is minimal (Torvanger & Ericson, 2013). Therefore, the export compression from Nyhamna is set to zero as the emissions linked to this operation is negligible compared to similar operations at other processing facilities. However, there are some emissions at the facility which can be linked to combustion such as flaring, boilers and engines used for processing operations and project activities. Resulting in an emission intensity for the processing operation of 1,775 kg CO_2 per Sm^3oe., which is the lowest among all the processing facilities on the NCS. The dry gas export pipeline Langeled transport the processed gas 627 km in 42” pipes to the Sleipner field before being sent the remaining 543 km through 44” pipes to the UK. The total carbon footprint for the chain amounts to 96,281 kg CO_2 per Sm^3oe. natural gas transported the 2.651 km from the Barents Sea to Easington in the UK, making it the best chain among the scenarios without development of a new processing facility.

2. Åsgard – Dornum

Operation	Unit emission intensity
Field	20,781
New Barents Sea pipeline	43,298
Existing pipeline	30,611
Processing	22,147
Export pipeline	16,054
Carbon footprint	**132,891**

In this scenario, there will be a new discovery equivalent to the Åsgard field located in the Barents Sea. The field is considered a giant gas field with an annual production volume of more than 17 billion Sm^3 natural gas and minor volumes of associated oil and condensate. Åsgard is a large field development consisting of Åsgard A which is an oil producing FPSO, the gas platform Åsgard B, and the storage vessel Åsgard C. In total, the field comprises of 56 production and injection wells. The gas production on Åsgard B consist of 14 templates including the reservoirs of Smørbukk, Midgard, Mikkel and Morvin. However, the field is powered by gas turbines which result in an emission intensity for the field operations of 20,781 kg CO_2 per Sm^3oe. Although most emissions are linked to the turbines, there are also considerable amounts that can be traced to flaring. Like the other scenarios without specific separation of power consumption we had to use the 40/60 split to extract the emissions from field operations.

The Barents Sea pipeline in this scenario is an extension of the Åsgard Transport pipeline. Therefore, we had to estimate the emissions per kilometre before multiplying it to get the emission intensity for the new 1.000 km pipeline from the Barents Sea. The resulting emission intensity for the new pipeline amounted to 43,298 kg CO_2 per Sm^3oe. With a diameter of 42” the pipeline has a capacity of 70 million Sm^3 of gas per day. The required power for compression to push the gas through the pipeline is generated by the turbines out on the field. The existing pipeline for the scenario is the 707-km long Åsgard Transport pipeline which will be the connection point for the new Barents Sea pipeline. The pipeline diameter and capacity is the same for both, and the gas is transported to the Kårstø processing facility in Rogaland. It is assumed that the pressure in the pipeline will be sufficient and that the gas will reach the processing facility without additional compression. The resulting emission intensity for the existing Åsgard Transport therefore amounts to 30,611 kg CO_2 per Sm^3oe. of gas flowing through it.

The processing at the Kårstø facility is an emission intensive operation and most of the power supply can be traced to turbine technology. However, the large volumes of gas that are processed (25% of Norwegian total) contributes to lowering the emission intensity to 22,147 kg CO_2 per Sm^3oe. There are nine compressors used for export operations at the facility, five of which powered by gas turbines and the remaining four by the mainland electricity grid. In this scenario, the processed gas is further shipped through the 658-km long Europipe II pipeline to Dornum in Germany with an emission intensity of 16,054 kg CO_2 per Sm^3oe. exported. The 42” export pipeline has a capacity of 71,2 million Sm^3 natural gas per day. The total carbon footprint of transporting natural gas over the 2.365 km from the Barents Sea to Germany accumulates to a total of 132,891 kg CO_2 per Sm^3oe.

3. Norne – Dornum

Operation	**Unit emission intensity**
Field	32,436
New Barents Sea pipeline	130,386
Existing pipeline	96,747
Processing	22,147
Export pipeline	16,054
Carbon footprint	**297,770**

The last scenario in this category of value chains without the establishment of a new processing facility consist of a new discovery in the Barents Sea equivalent to the Norne field. The field produce considerable amounts of oil and gas, but also considerable amounts of emissions due to the extensive utilisation of turbine technology. However, this is the only field which has a clear reported distribution of power requirements for field operations and gas transportation with the respective split of 35/65 (Shaton, 2017). The resulting emission intensity for the field operations can therefore be estimated to 32,436 kg CO_2 per Sm^3oe. natural gas produced. More than 94% of the emission can be traced to the exhaust gases from the turbines of which 35% from older SAC turbines and 65% from DLE, which also corresponds to the split and indicate that the latter is used for gas transport.

The new Barents Sea pipeline in this scenario is based on the 128 km Norne gas transport system connected to Åsgard Transport by 16” pipes. The smaller diameter only has a capacity of seven million Sm^3 natural gas per day. The relatively low volume combined with the high emissions from gas transport results in an emission intensity of 130,386 kg CO_2 per Sm^3oe. when scaling up the pipeline to 1.000 km. Connecting the extended Norne gas transport system to the existing Åsgard Transport pipeline to send the gas to Kårstø for processing also create a substantial emission intensity of 96,747 kg CO_2 per Sm^3oe. The distribution of emissions between the new Barents Sea pipeline and Åsgard Transport is difficult to guarantee due to the differences in diameter but the total would amount to 227,133 kg CO_2 per Sm^3oe. The calculations used to separate the emission intensities in this case were purely based on distances and may therefore be somewhat inaccurate.

However, when the gas reach the Kårstø processing facility the emission intensity will be the same (processing 22,147 kgCO_2/Sm^3oe. and export pipeline 16,054 kgCO_2/Sm^3oe.) as in the previous scenario. The total carbon footprint for transporting natural gas over the 2.400 km from a new discovery equivalent to the Norne field to Dornum in Germany will therefore amount to 297,770 kg CO_2 per Sm^3oe.

6.2.2 Category 2: Pipeline chains with a new processing facility

Two value chains have been included in this category to cover the carbon footprints of establishing a new facility in Nordland county receiving Barents Sea gas before sending the processed dry gas to existing infrastructure further south on the NCS.

Table 6 Category 2 value chain description.

Field	Upstream transportation	Processing (Nordland)	New export pipeline to Sleipner field	Existing export pipeline
Ormen Lange	700 km Field dedicated 30” pipeline	New Nyhamna processing facility	1000 km Langeled 42” pipeline	Sleipner Vest 813 km Zeepipe 40” Zeebrugge
Åsgard	707 km Åsgard Transport 42” pipeline	New Kårstø processing facility	1000 km Europipe II 42” pipeline	

4. Ormen Lange – Zeebrugge

Operation	Unit emission intensity
Field	0,000
Upstream transportation	0,000
Processing	1,775
New export pipeline	0,000
Existing export pipeline	35,229
Carbon footprint	**37,004**

A new discovery equivalent to the size and configuration of the Ormen Lange gas field is included in this scenario. Ormen Lange is only second to the Troll field on the NCS when accounting for gas reserves and is situated in the Norwegian Sea on depths ranging from 850-1.100 metres. Despite being recognised as a gas field, Ormen Lange also produce volumes of light oil equivalent to a medium sized oil field. Its reservoir stretches across 350 km^2 and gas is produced through 24 wells distributed among four subsea templates. Being developed with subsea structures powered by clean energy from the new processing facility equivalent to Nyhamna it will basically have zero emissions related to general field operations. However, the existing Ormen Lange field is only located 120 km from shore which simplifies the use of PFS technology. In our case, the new processing facility is located somewhere along the shores of Nordland far from the Barents Sea. The question is whether it is possible to have full electrification of a field located that far from shore and processing facilities. The field with the longest distance from shore with full electrification today is the Valhall complex with a sea-cable covering 292 km (Westman, Gilje, & Hyttinen, 2010). In our case, it is assumed that R&D on PFS-technology will be sufficient to overcome this obstacle and supply a field of up to 700 km with power from shore. This should be a possibility considering the Nexans NordLink-project which will cover 700 km off the coast of Norway and Denmark with high voltage direct current cables, like those used for the Valhall complex (Nexans, 2015). Therefore, both the field operations and upstream transportation in this scenario will be powered through sea-cables from the mainland electricity grid with the Norwegian el-mix (27 grams of CO_2 per kWh), and the emissions is therefore set to zero. With the gas being brought to shore by a 700 km 30" pipeline and processed at the new Nyhamna facility, the emission intensity will be the same as for the existing one, resulting in only 1,775 kg CO_2 per Sm^3oe.

Considering the export pipeline from Nyhamna, the emissions are integrated in the facility and hard to separate, and is therefore also set to zero. The new export pipeline will transport the processed dry gas from the new facility in Nordland to the Sleipner field. The dimension and capacity for the new export pipeline will have the same design and capacity as Langeled, which is a 42" pipeline with a capacity of 74,7 Sm^3 per day. It is assumed that the distance from the processing facility to Sleipner is 1.000 km and that the pipeline pressure needs to be increased at Sleipner to reach Zeebrugge. Therefore, the emission intensity for the existing export pipeline obtained is 35,229 kg CO_2 per Sm^3oe, and will be the largest contributor to emissions in this chain. The total carbon footprint for the 2.513 km distance results in 37,004 kg CO_2Sm^3oe, which is the best case by far compared to any other scenario in the analysis. However, there is a lot of uncertainty related to the possibility of such a comprehensive utilisation of PFS-technology with respect to the capacity in the mainland electricity grid and the long distances. It is also important to remember that the emissions for the field operation, upstream transport and new export pipeline will be more than zero when accounting for their actual energy demand and the 27 gram CO_2 per kWh consumed.

5. Åsgard – Zeebrugge

Operation	Unit emission intensity
Field	20,781
Upstream transportation	30,611
Processing	22,147
New export pipeline	24,398
Existing export pipeline	35,229
Carbon footprint	**133,167**

In this scenario, there will be another new discovery equivalent to the Åsgard field with the same emission intensity as in the previous Åsgard scenario. However, rather than extending the Åsgard Transport pipeline further north, the rich gas is here brought to a new onshore processing facility in Nordland. Nevertheless, the emission intensity for the field operation remain the same 20,781 kg CO_2 per Sm^3oe.

After being extracted the rich gas is sent through an upstream pipeline equivalent to the existing 707 km Åsgard Transport pipeline to the new processing facility. The upstream transportation therefore has an emission intensity of 30,611 kg CO_2 per Sm^3oe. In this scenario, it is assumed that there is limited capacity in the onshore power grid and the facility is therefore equivalent to the Kårstø facility where much of the power supply come from turbine technology. This fact is resulting in an emission intensity for the processing operation of 22,147 kg CO_2 per Sm^3oe. The processed dry gas is exported through a new export pipeline from the facility to the existing Sleipner field. Due to this fact, the existing Europipe II pipeline is scaled up to 1.000 km which assumed to be the approximate distance the dry gas needs to cover to reach the Sleipner field, increasing the new export pipeline emissions to 24,398 kg CO_2 per Sm^3oe.

When the gas reach the Sleipner field it has already been shipped 1.000 km from the processing facility and it is assumed that the gas will require additional compression to cover its final leg to Europe. In Shaton´s (2017) research, the figures for export compression at Sleipner – Øst and Vest were respectively 40,21 and 41,68 kg CO_2 per Sm^3oe. However, our estimates with 2015 data provide respective emission intensities of 60,434 and 35,229 kg CO_2 per Sm^3oe. transported, and we have only included the latter Sleipner Vest due to the lower emission intensity. From Sleipner the dry gas is transported through the 40” diameter and 813 km long Zeepipe pipeline to Zeebrugge in Belgium with a capacity of 42,5 million Sm^3 gas per day. The carbon footprint for this value chain amounts to a total of 133,167 kg CO_2 per Sm^3oe. transported over 2.520 km before reaching its destination.

6.2.3 Category 3: LNG Chain

Only one LNG chain has been included in the analysis to provide a comparison against the previously described pipeline chains. The LNG chain is hypothetical with respect to its destination to get a comparison of the emissions over the same distances from the field to the market.

Table 7 Category 3 value chain description.

Field	**Upstream Transportation**	**Processing Liquefaction**	**Export**	**Destination**
Snøhvit	143 km Field dedicated 26” pipeline	Melkøya LNG Hammerfest	LNG carrier 2.547 km sailing distance	Zeebrugge BEL

6. Snøhvit – Zeebrugge

Leading up to the transportation stage of LNG from Melkøya in Hammerfest to Zeebrugge in Belgium, the configuration of the chain represents the existing configuration of the only large scale LNG operation on the NCS.

Operation	**Unit emission intensity**
Field	0,000
Upstream transportation	0,000
Processing	29,001
Liquefaction	111,918
LNG carrier	51.646
Carbon footprint	**192,565**

Snøhvit is a giant gas field also containing condensate located in the Hammerfest basin in the Barents Sea on depths ranging from 310-340 metres. The discovery was made in 1984 but did not come on stream before 2007, nevertheless making it the first gas field development in the area. The field consists the discoveries Snøhvit, Askeladd and Albatross, and gas is produced through 20 wells from subsea structures. The wellstream is sent through a multiphase pipeline for processing at the Melkøya LNG. The production volumes for 2015 amounted to about 7,1 billion Sm^3 natural gas and 0,9 million Sm^3 condensate. The fact that the field is powered from the onshore facility, the emissions from field operations and upstream transportation is included at Melkøya LNG and therefore set to zero in our analysis. However, the facility is utilising turbine technology so the actual emissions if separated would be substantial.

The Statoil operated LNG facility located outside Hammerfest in Finnmark county is the only of its kind in Norway and came on stream at the same time production commenced at Snøhvit. Rich gas from the field is brought onshore for initial processing and liquefaction before being exported by designated LNG carriers. The well stream is transported by a 143km pipeline to the facility where the gas is processed and cooled to its liquid form as LNG. The well stream contains considerable amounts of CO_2 which is separated before being reinjected back into formations in the Snøhvit reservoir. At the Melkøya facility the final products being shipped to their respective markets are LNG, condensate and LPG. The processing facility requires significant amounts of energy and is self-sufficient using five gas turbine generators type LM6000 DLE from general electric. Each of which with a performance capacity of 45 MW that easily can satisfy the total power requirement of 215 MW.

In the Shaton (2017) framework, it is assumed that there is a separation of the power consumption related to the operations of initial processing and liquefaction with a respective split of 10/90. Resulting in a unit emission intensity for the processing of the wellstream before liquefaction of 29,001 kg CO_2 per Sm^3oe. This is relatively low and can most likely be linked to the fact that the separated CO_2 from the wellstream is injected back into formations in the Snøhvit reservoir rather than vented to air. The liquefaction stage is a much more energy intensive operation, especially related to the energy required for cooling the gas, and generates a unit emission intensity of 111,918 kg CO_2 Sm^3oe.

After processing and liquefaction, the final product of LNG is loaded onto specialised LNG carriers for transportation. The sailing distance from Melkøya to Zeebrugge is approximately 2.547 km and is a relatively short distance for LNG carriers. However, to get a comparison of emissions to the pipeline chains we found it beneficial to apply the same distances to make it comparable. As the estimations of exact emissions from LNG carriers is very complex with many variables it is considered outside the scope and timeframe of this research. However, using the Psaraftis & Kontovas (2009) emission estimate with 13 gram CO_2 per ton-km (transporting one ton of LNG one km) we can simplify the task of obtaining the emissions for the shipping distance from Melkøya to Zeebrugge. Based on the LNG carrier the Arctic Princess (Skipsrevyen, 2007) which has a cargo capacity of 147.000 Sm^3 LNG, equivalent to 66.150 ton, the calculations would be the following:

$$Unit\ Emission\ Intensity = \frac{kg\ CO2\ per\ ton\ km\ *\ ton\ LNG\ *\ km\ sailing\ distance}{Sm3\ LNG * expansion\ ratio}$$

The emissions for the sailing distance one way from Melkøya to Zeebrugge result in 25,823 kg CO_2 per Sm^3oe., but if we assume that the vessel would have to return to Melkøya before the LNG carrier operation is finalised the emission intensity would be doubled to 51.646 kg over the distance of 5.094 km. The expansion ratio is based on the Norwegian LNG characteristics where 1 Sm^3 LNG expands to 577 Sm^3 natural gas during regasification (International Gas Union, 2012). The total carbon footprint for the Snøhvit – Zeebrugge LNG chain therefore results in an emission intensity of 192,565 kg CO_2 per Sm^3oe. transported over a total distance from the wellhead to the market of 2.690 km.

6.3 Results

Table 8 Value chain carbon footprint and distance.

Category	Value chain	Carbon footprint (kg CO_2/Sm^3oe)	Distance (km)
1. Pipeline chains without new processing facility	1. Aasta Hansteen - Easington	96,281	2.651
	2. Åsgard - Dornum	132,891	2.365
	3. Norne - Dornum	297,770	2.400
2. Pipeline chains with new processing facility	4. Ormen Lange - Zeebrugge	37,005	2.513
	5. Åsgard - Zeebrugge	133,167	2.520
3. LNG chain	6. Snøhvit - Zeebrugge	192,565	2.690

Investigating the total carbon footprints among the chains included in the analysis, it becomes clear that the value chains characterised by a higher utilisation of PFS-technology generate the least amount of emissions. However, there are other factors that influence the amount of emissions in the different categories of value chains as well. For Category 1, the pipeline chains without the establishment of a new processing facilities, most of the emissions can be traced to the new Barents Sea pipeline, ranging from 33-55% of the total carbon footprint in each chain. And for the two scenarios in which a new facility is established, most of the emissions is linked to the export transportation from the new processing facility to the market with 45% and 95% out of the total. For both categories, it becomes evident that the distances to the market has a significant impact on the emission intensity for the pipeline chains. However, despite what is recognised as a long distance for pipelines to travel, the LNG chain is very short in a global perspective. Nevertheless, several of the pipeline chains outperform the LNG chain with only the 3. Norne – Dornum chain performing worse. This fact can be traced to the energy intensive liquefaction process at the LNG facility, which accounts for 58% of the total emissions per delivered

Sm^3oe. of natural gas. Also, the fact that the LNG carrier must travel twice the distance to both deliver cargo and returning in ballast opens for an interesting discussion. Since the volume of cargo is fixed by the vessels cargo carrying capacity, the unit emissions for the LNG carrier would only continue to increase if the LNG chain were to be any longer. Considering only the emissions, it is not certain that the LNG chain would outperform the best pipeline chain if the distances were to be any longer. Also, the fact that all the pipeline chains included in the analysis is shorter than the LNG chain, they would most likely not be performing worse than the LNG chain if the distances were to be the, same given the resulting carbon footprints obtained through the analysis.

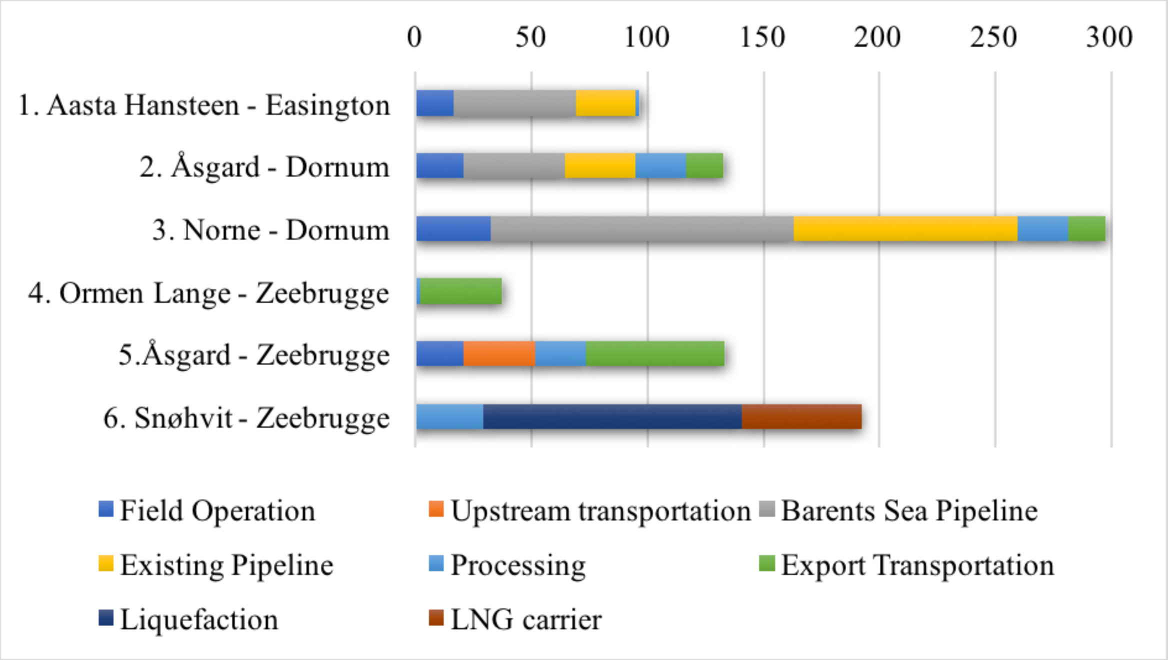


Figure 6 Value chain emission intensity (kg CO2 per Sm3oe.).

When comparing the six value chains investigated through the analysis it is evident that utilising PFS-technology and turbines constitute major roles when it comes to the emission intensities. Development of fields that are powered from shore and connected to the main electricity grid have only minor emissions when comparing them to the fields with turbines as a powering source. The same applies for the processing facilities which can be seen at Nyhamna where the emissions are only minor when comparing them to Melkøya or Kårstø. Connecting the new fields in the Barents Sea to existing infrastructure is the stage in the analysis with the most uncertainty connected to it. In the analysis, it is assumed that pipelines equivalent to existing pipelines will be developed to connect the fields to existing pipelines or new processing facilities. The emission intensity for the Åsgard Transport pipeline is higher than Polarled which becomes evident when deciding where to connect to existing infrastructure. After being connected to existing infrastructure, the gas will flow through the existing network to its destination. It is important to remember that the existing pipeline network on the NCS can send gas to several destinations and that gas from different fields can be mixed and sent wherever gas is demanded. To summarise, the carbon footprint for the value chains transporting natural gas from the Barents Sea to the European market is closely related to the energy source utilised to satisfy their demand for energy. Knowing that the energy demand for gas fields tend to increase throughout their lifecycle, it can be expected that the emission intensities presented will increase as well, especially for the chains dependent on turbine technology.

7 Putting a Price on the Carbon Footprints

In the carbon footprint analysis, we established six value chain scenarios to illustrate and highlight the potential carbon footprints of production and transportation from offshore fields in the Barents Sea to the European market. This chapter will focus on pricing these emissions with respect to the two-degree target and the recent Paris Agreement to see what their costs can amount to.

The objective of a carbon price is to correct market failure by covering the negative externality that occurs when economic activities emit CO_2 into the atmosphere. In competitive markets where negative externalities are evident and not covered, there is a gap between the marginal social cost curve and the marginal private cost curve. This will result in a deadweight loss and lead to decreased net social benefit for society. The marginal cost of producing oil and gas on the NCS today includes a carbon price to cover for the externality. It is uncertain whether the current carbon price fully covers the externality associated with the petroleum activity and many argue that it is only marginal compared to the actual costs of the carbon emissions. However, the exact cost of carbon emission is hard to quantify. The marginal social cost includes both the marginal private cost and the exact price of carbon emissions and there are two approaches to internalise the externality. The first is to put price equal to the marginal cost of damage, which is referred to as a Pigou tax. There are methodological and ethical challenges to calculate such a price. The second approach is to make an implicit valuation, where the carbon price equals a price that governments can accept corresponding to binding mitigations targets (Volden, 2013). The graph below illustrates the gap between the marginal social cost curve (MSC) and the marginal private cost curve (MPC) and show how the negative externality occurs, represented by the grey triangle. A more precise carbon price could minimise the negative externality by reducing the gap between the two curves.

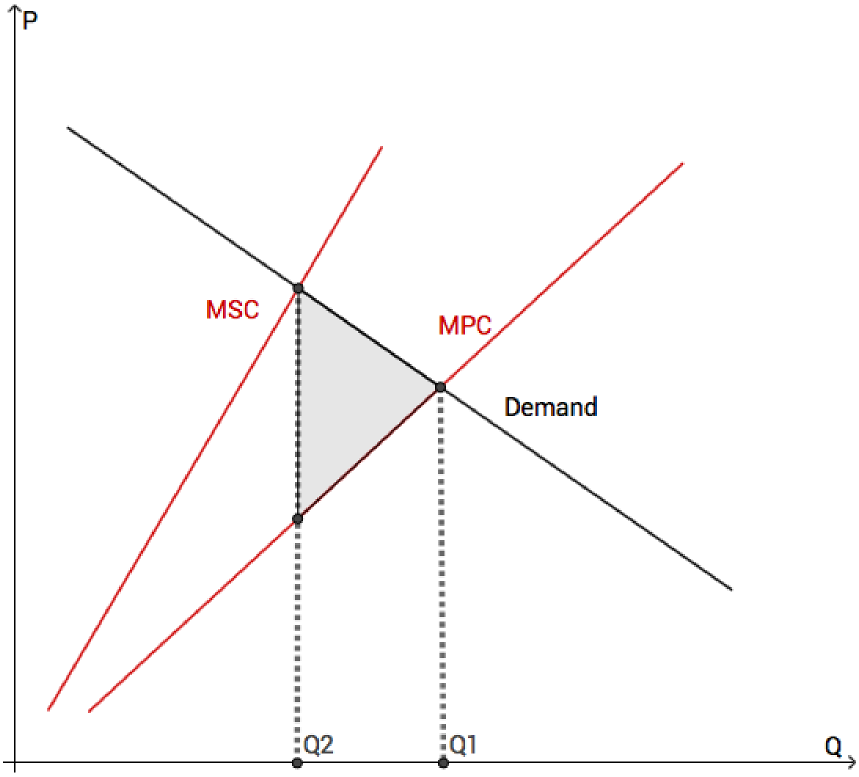


Figure 7 Illustration of a negative externality.

When investigating the cost of carbon pricing on the established value chain scenarios, we use two prices, which represent the carbon prices in the MSC and MPC.

The carbon price which represent the social cost of carbon emission is set to be a new uniform global carbon price corresponding to the two-degree target set by the Paris Agreement. Scientists and organisations have attempted to estimate several so-called “two-degree carbon prices”. For simplicity, we applied the carbon price presented in the Norwegian climate report KlimaKur 2020, which state that a price per ton of CO_2 should amount to 100 euro by 2030 to be able to maintain the two-degree target. With an exchange rate of 1 EUR = 9,5023 NOK (May 5th 2017), the carbon price amounts to 950,23 NOK per ton CO_2, and 0,95023 NOK per kg which is the unit of measure used in the carbon footprint analysis. This two-degree carbon price act as our implicit valuation of the externality associated with CO_2 emissions. However, the accuracy of this carbon price is uncertain and the feasibility of establishing a global price covering all sectors and emission might also be considered impossible. Nevertheless, a uniform global carbon price provides a good basis for an interesting discussion regarding impacts and effects on the obtained value chain scenarios´ carbon footprints. The current Norwegian carbon price represents the private costs the participants on the NCS face today, which in total amounts to 494,97 NOK per ton of CO_2. About 445 NOK is related to the Norwegian carbon tax, while the remaining 49,97 NOK is the quota price in EU-ETS. It is expected that the Paris Agreement will intensify the global measures to mitigate carbon emissions, thus reducing the gap between the actual cost of emissions and what the polluters are currently paying for their emissions.

With the petroleum activities on the NCS being subject to both the Norwegian carbon taxation and the EU-ETS, and about 80% of all Norwegian emissions covered by these two schemes. The emissions included in the carbon footprint analysis will therefore be subject to both the Norwegian carbon tax and the EU-ETS, further denoted by the Norwegian carbon price.

Table 9 Value chain annual production volumes and emissions.

Value Chain	**Annual production volumes**	**Carbon Footprint**	**Annual CO_2 emissions in ton**
1. Aasta Hansteen - Easington	5 166 667	96,281	497 452
2. Åsgard - Dornum	17 477 768	132,891	2 322 638
3. Norne - Dornum	2 346 178	297,77	698 621
4. Ormen Lange - Zeebrugge	16 791 486	37,004	621 352
5.Åsgard - Zeebrugge	17 477 768	133,167	2 327 462
6. Snøhvit - Zeebrugge	7 077 457	192,565	1 362 871

The table above show the total annual production volumes together with the carbon footprints of the value chains which results in the total amount of ton CO_2 emitted per year. As we can read from the table, the emissions are significant and will constitute a great share of the total emissions in Norway and on the shelf. With respect to the reported figures for 2015, where the emissions from petroleum activities amounted to a total of about 13,5 million ton CO_2 (Norskpetroleum, 2017a). The value chains with the most emissions would constitute as much as 17% of this total, when considering any of the new Åsgard chains.

Considering the latest resource estimates projected NPD it will be reasonable to assume that more than one new chain will have to be developed. The chains included in the analysis only represents a total volume of about 66 billion Sm^{3}oe., while the new projections consist of 1.400 billion Sm^{3}oe (Norwegian Petroleum Directorate, 2017). However, this total of hydrocarbons is not solely represented by natural gas but it shows that it will become necessary with additional value chains than the ones included in our analysis, or a combination of these to transport large volumes of Barents Sea gas.

Table 10 Carbon prices in NOK per Sm3oe. from the value chains.

Value chain	**Subject to carbon pricing**	**New global carbon price**	**Norwegian carbon price**
1. Aasta Hansteen - Easington	96,281	91,49	47,66
2. Åsgard - Dornum	132,891	126,28	65,78
3. Norne - Dornum	297,770	282,95	147,39
4. Ormen Lange - Zeebrugge	37,005	35,16	18,32
5. Åsgard - Zeebrugge	133,167	126,54	65,91
6. Snøhvit – Zeebrugge (LNG)	192,565	182,98	95,31

Knowing the carbon footprint for each of the value chains and the cost per ton CO_2, we easily obtain the cost of the unit emissions per Sm^{3}oe. Comparing the new global carbon price and the Norwegian carbon price it becomes clear that the industry will experience a significant increase with almost a doubling per Sm^{3}oe. produced and transported. However, it can also be observed that the new carbon price for some of the value chains still will be lower than the existing price for the worst-case value chain scenarios. For example, we see that the new global carbon price for the 4. Ormen Lange – Zeebrugge chain of 35,16 NOK per Sm^{3}oe. still will be considerably lower than the existing Norwegian carbon price for all the other chains.

To further investigate the impact of carbon pricing on the value chains we have chosen to include one scenario from each of the value chain categories explained in the carbon footprint analysis. The scenario from Category 1 included is the 2. Åsgard – Dornum value chain. This is the value chain in which a new discovery of the same size and specification as Åsgard will be developed in the Barents Sea. The field exports the rich gas through an extension of the Åsgard Transport pipeline which will act as the new Barents Sea pipeline.

When reaching the existing infrastructure, the rich gas is brought to Kårstø for processing before further export to Dornum in Germany.

Table 11 Category 1 value chain.

2. Åsgard - Dornum	**Unit emission intensity**	**Annual CO_2 emission in ton**	**Cost of new global carbon price**	**Cost of Norwegian carbon price**
Field	20,781	363 206	345 128 766	179 777 574
New Barents Sea pipeline	43,298	756 752	719 088 847	374 573 380
Existing pipeline	30,611	535 012	508 384 422	264 817 445
Processing	22,147	387 080	367 815 158	191 594 916
Export pipeline	16,054	280 588	266 623 224	138 884 037
Carbon Footprint	**132,891**	**2 322 638**	**2 207 040 417**	**1 149 647 353**

Considering the volume of natural gas produced at the Åsgard field together with the emission intensities for the various operations included in the value chain, the resulting CO_2 emissions becomes massive. A total of more than 2,3 million ton CO_2 is emitted over the course of a year in this chain. Today, these emissions would be priced by the Norwegian carbon tax and EU-ETS at more than 1,1 billion NOK. However, with the new global carbon price corresponding to the two-degree-target in 2030, these emissions would come at a cost of more than 2,2 billion NOK.

The scenario included from Category 2 is the 4. Ormen Lange – Zeebrugge chain, which also is the best-case scenario in our carbon footprint analysis. The value chain consists of a new field in the Barents Sea equivalent to the existing Ormen Lange field. The rich gas is transported to a new processing facility in Nordland equivalent to the existing Nyhamna facility. The processed dry gas is further transported by a new export pipeline to the Sleipner field before being sent through the existing export pipeline to Zeebrugge in Belgium.

Table 12 Category 2 value chain

4. Ormen Lange - Zeebrugge	**Unit emission intensity**	**Annual CO_2 emission in ton**	**Cost of new global carbon price**	**Cost of Norwegian carbon price**
Field	-	-	-	-
Upstream transportation	-	-	-	-
Processing	1,775	29 805	28 321 499	14 752 669
New export pipeline	-	-	-	-
Existing export pipeline	35,229	591 547	562 105 965	292 800 997
Carbon Footprint	**37,004**	**621 352**	**590 427 464**	**307 553 666**

Although the 4. Ormen Lange – Zeebrugge is the best case among the scenarios included in the analysis, there are still considerable amounts of emissions generated throughout the chain. As previously explained, emissions related to the field, upstream transport, and export transport are integrated in the processing facility which act as the powering source for the operations. With a production and transportation of almost 17 million Sm^3oe. natural gas per year, the total CO_2 emitted into the atmosphere amounts to more than six hundred thousand tons. However, compared to the other chains included in the analysis this seem reasonably modest. Putting a price on the current emissions from this chain amounts to more than 300 million NOK. Leading up towards 2030, with the establishment of a global carbon price, these costs will increase towards 590 million NOK.

The final scenario we investigate is the Category 3 LNG chain 6. Snøhvit – Zeebrugge. This is the only LNG chain included in the analysis but serves the purpose of comparing the pipeline chains towards other modes of transportation for large volumes of natural gas. The natural gas in this chain travel from the Snøhvit field as rich gas to Melkøya LNG for initial processing and liquefaction. After being transformed into LNG, the gas is loaded onto LNG carriers before being shipped to Zeebrugge.

Table 13 Category 3 value chain

6. Snøhvit - Zeebrugge	**Unit emission intensity**	**Annual CO_2 emission in ton**	**Cost of new global carbon price**	**Cost of Norwegian carbon price**
Field	-	-	-	-
Upstream transportation	-	-	-	-
Processing	29,001	205 253	195 037 875	101 595 229
Liquefaction	111,918	792 095	752 672 282	392 066 992
LNG carrier	51,646	365 522	347 330 301	*180 924 354*
Carbon Footprint	**192,565**	**1 362 871**	**1 295 040 458**	**674 586 574**

When it comes to carbon footprints, the LNG chain is one of the most emission intensive among the scenarios included in our analysis, with only the 3. Norne – Dornum chain performing worse. The liquefaction process alone generates almost eight-hundred thousand ton CO_2 over the course of one year at a cost of more than 750 million NOK considering the new global carbon price.

The emission intensity related to the shipping by LNG carriers is also substantial in terms of tons of CO_2 emitted on an annual basis. An interesting discussion surrounding the current situation is that these emissions are not covered by the Norwegian carbon tax, nor the EU-ETS, and international shipping is neither included in the Paris Agreement. Meaning that almost 27% of the total carbon footprint is not paid by the emitter, equivalent to more than 180 million NOK per year.

The discussion surrounding the expansion of Melkøya with a second LNG train is assumed to result in the exact same emission intensity as the current level. The reasoning behind this assumption is that all emissions related to field-, processing- and liquefaction operations will be doubled together with a doubling of the volume of gas produced, which result in the same carbon footprint for the chain. If to be included in this investigation, the resulting emissions and cost of carbon pricing would only be doubled. However, since the carbon footprint will remain the same as the current situation it is not displayed in our tables.

8 Impacts on the Norwegian Gas Supply

By analysing the theory presented in the former chapters together with the carbon footprints and carbon pricing, in a competitive advantage point of view, one can highlight several key factors that distinguishes Norwegian gas supply from other gas providers. Our attention has solely been concerned with the European gas market, with the focus being on future demand in a time of increasing attention to mitigation policies. This determines and limit the scope of our investigation. We highlight four characteristics of the Norwegian gas supply**,** which underlines the competitive advantages, and assess how our research impacts these.

1 Long-term and robust supply

The first aspect is concerned with the physical supply of Norwegian natural gas to Europe. Export of natural gas from the NCS had its beginning in 1977 (Austvik, 2013), and more than 40 years of continuous supply is a unique feature which have provided Europe with a low risk of supply. Figures from Gassco show a 99,71% deliverability of the volume requested in 2016, which also entails a low supply risk. As seen in the study by Belkin et. al., (2013) the Russian gas supply is associated with a higher supply risk, where political instability between Russia and European countries in the past has caused abruptions in the gas supply. Political stability provides robustness to the Norwegian supply, which Europe benefits from in terms of risk allocation. Since natural gas is a vital commodity being exploited in many sectors, the supply chain risk is a key determinant and will in turn increase the competitive advantages of Norwegian gas supply.

For Norway to maintain its current annual export level of around 100 billion Sm^3 in the years to come, the Barents Sea must be further developed, as of the declining trend in production from existing fields further south on the shelf (Norskpetroleum, 2017b). The value chain scenarios presented in the carbon footprint analysis show how Norway can maintain exports levels by adding Barents Sea resources to existing natural gas transport infrastructure.

2 Integrated in the EU

The second aspect address the relationship between the Europe and Norway. The liberalisation agenda by the EU have historically set restrictions regarding gas sales. Norway have complied with EU regulations since their proposed directives of the early 1990's, which objectives was to create an internal and more competitive gas market. Agreements of the last directive, the "Gas Directive" in 2001, resulted in a structural shift for Norwegian gas sales. An introduction of third party access, led to the unbundling of gas transport and sale. As a result, the NCS operate with the appointed neutral TSO Gassco, which in turn generates a higher net social benefit and competitiveness to secure low commodity prices and security of supply to the EU. This feature creates free movement of gas between the supplier of natural gas and the consumers (Austvik, 2003; Andersen & Sitter, 2009). Third party access is not evident in Russia, where Gazprom act as a monopolist for all gas transport. This structure leads to market inefficiency, where a deadweight loss will occur. Gazprom have the possibility to exercise market power towards the consumers, thus imposing a risk of supply for the European market. The Norwegian petroleum production have in addition been part of the EU-ETS since 2008. This means that the emissions from the NCS are subject to a scheme established by the consumers and that the gas supply coincides with EU's requirements concerning emissions. In a near future where carbon pricing is predicted to increase, EU can obtain overall control of the emissions and make sound mitigation measures to efficiently decrease emissions in line with binding mitigation targets set by the Paris Agreement. Norwegian gas will thus operate on EU's premises.

If Norway were to produce and transport from new fields in the Barents Sea, the gas would be subject to the EU-ETS and if a pipeline solution is selected, the gas transport will continue to act according to EU's regulations.

3 Infrastructure already paid off

The NCS have since its beginning developed an extensive infrastructure network, which connect fields, processing facilities and receiving terminals in an efficient way. Since much of the infrastructure on the southern part of the NCS is already in place, it makes potential connection to the Barents Sea easier. As elaborated above, potential new pipeline solutions will be connected to the existing pipeline network. The transportation tariff embodied by Norwegian law include a capital element to cover the investment costs and since much of the infrastructure have been operating for several decades, the capital element is very low for large parts of the existing infrastructure. This aspect ensures low transportation costs for the users of the transport infrastructure.

Our analysis show that extending the pipeline network and connecting it to potential gas deposits in the Barents Sea can be a cost-efficient solution due to the already low cost in the older infrastructure further south on the shelf. The low transport cost may in turn offset the predicted intensification of carbon pricing.

4 Low environmental footprint

It is evident from the theory that the average CO_2 emissions per unit of oil and gas produced in Norway is well below the global average measures from the IOGP members. Emission data from Gavenas et. al., (2015) show that the Norwegian average was 55 kg CO2 per ton oe., whereas the emission figures obtained from IOGP (2016) show a global average among the members of 129 ton CO2 per thousand ton oe. (equal to 129 kg CO2 per ton oe.). When comparing the emissions per unit produced for the different petroleum regions, it becomes clear that the Norwegian oil and gas production have low environmental footprints compared to other suppliers. Norwegian oil and gas production only generate about 40% of the total global CO_2 emissions per unit and around 60% of the average in Europe, which is the relevant gas market for this study. There is a significant difference and in a transition to a low carbon society, this gives Norwegian oil and gas a competitive advantage in terms of more environmentally friendly supply chains. However, based on the empirical data provided in the dissertation, it is hard to determine whether Norwegian production possess the cleanest production, due to the uncertainty of the figures. Nevertheless, one can conclude that Norwegian production is one of the most environmentally friendly. The LNG facility in Hammerfest was stated by Glave & Moorhouse (2013) to have the cleanest LNG production in the world. Although there is not sufficient scientific research to back up this statement, one can assume that the emission level is among the best. An explanation to the low energy intensity on the NCS were by Gavenas et. al., (2015) pointed towards the combination of the imposed CO_2 tax together with EU-ETS regulations. According to Porter’s hypothesis (Porter & Linde, 1995), strict regulations will give economic incentives, which result in innovation and higher efficiency, thus leading to competitive advantages. Porter’s hypothesis seems to be evident in the case of Norwegian petroleum production where mitigation technology such as PFS- and CCS technology has risen in line with strict environmental regulations in form of carbon taxations, petroleum acts and laws.

The analysis show that a new global carbon price of 100 euro per ton CO_2 generates high costs for the polluters. The value chains which entail the lowest emission cost will have a competitive advantage in a future of high carbon pricing in the EU. This will in turn strengthen Norway´s position as an energy efficient provider of natural gas. When comparing the production figures presented earlier with our carbon footprints by converting ton oe. to Sm^3 oe., (one ton oe. equals 1,166 Sm^3 oe.), the Norwegian average becomes 47,17 kg CO_2 per Sm^3 oe. and the IOGP average of 110,635 kg CO_2 per Sm^3 oe. As highlighted in the best-case scenario 4. Ormen Lange – Zeebrugge, value chains from the Barents Sea could operate with a very low carbon footprint and further strengthen the environmental advantage. Our best-case scenario yielded about 10 kg CO_2 per Sm^3 less for the entire value chain, than the production average for Norway and 73,631 kg CO_2 per Sm^3 less than IOGP figures. As for the LNG chain, Glave & Moorhouse (2013) figures could indicate that the carbon footprint from our LNG scenario 6. Snøhvit – Zeebrugge is low compared to others.

These four aspects highlight the main competitive advantages that the Norwegian gas supply possess and our research show how potential developments in the Barents Sea can further strengthen these. The characteristics presented above will be vital in a time where Europe intensifies their environmental mitigation policies.

9 Concluding Remarks

The overall aim of the research was to advance the understanding of the impact of carbon pricing on Norwegian natural gas supply, focusing on gas produced and transported from the Barents Sea to Europe. Through a comprehensive review of literature together with the carbon footprint analysis we have identified and described the emissions present in future potential Norwegian natural gas value chains. The case we highlighted in the research was the emissions from production from new value chains connecting Barents Sea gas to the European market. By putting a price on these emissions equivalent to the global two-degree target and the Paris Agreement we obtained the actual costs to be paid by the polluter. Linking the carbon footprints from the value chains to the impact of carbon pricing policies introduced a whole new field of research. Given the findings we could further highlight and strengthen the competitive advantages for Norwegian gas supply.

To answer the overall research problem for the study we initially drafted three specific research objectives that corresponded to the aim of that we were trying to achieve with the thesis.

By ***identifying*** the emissions from the value chain scenarios presented in the carbon footprint analysis we displayed the main drivers and possible obstacles for transporting natural gas produced in the Barents Sea to the European market. The findings showed that the main drivers for emissions could be traced to power generation together with a comprehensive utilisation of turbine technology throughout several stages of the chains. The demand for power generation was in turn driven by the most energy intensive operations, such as long distance pipelines- and LNG carrier transportation, and processing- and liquefaction operations. However, we also discovered the possibilities that PFS-technology could induce on the emissions from the value chains. The large share of renewable hydropower in Norway introduces the possibility of having close to minimal emissions from all operations powered by the mainland electricity grid.

Using the obtained carbon footprints from the different value chain scenarios we ***explored*** the impact of a carbon pricing policy corresponding to the two-degree-target and the recent Paris Agreement. Knowing that the emissions were priced per ton CO_2 emitted, the cost of the emissions would be directly linked to the energy efficiency in the value chain scenarios. Meaning that the differences in carbon footprints among the chains would result in the same difference when putting a price on the emissions. Accounting for the total volumes produced and transported, the differences in unit emission intensities had significant impacts on the total cost of the emissions. Comparing the best- and worst case scenarios, the difference in the cost per Sm^3 were almost 250 NOK which constituted costs in billions when producing and transporting annual volumes. This research objective was also the one that linked the carbon footprints from the value chain scenarios to carbon pricing, and is what have made this research an important contribution to a field of little or no existing research.

After linking the emissions from the value chain scenarios to the theory of carbon pricing policies we ***addressed*** the competitive advantages for Norwegian gas supply, and how the study further could strengthen these. Together with the direct impact on the value chains we discussed the impact on the future Norwegian gas supply to Europe in a more generic context. The main observations from the findings could be summarised to that: (1) Future gas resources from the Barents Sea could prolong the time-horizon of Norwegian gas exports and continue to provide Europe with a robust and long-term supply; (2) Barents Sea gas would also be subject to the EU-ETS, which gives EU the possibility to import gas, while still controlling the emissions; (4) Our findings further showed that new infrastructure development would benefit from connecting to the existing gas transport infrastructure further south on the shelf, providing EU with lower tariffs for transportation; And (4), the Norwegian possibility of developing value chains with low environmental footprints.

9.1 Limitations and Further Research

Being a very large topic, the investigation of emissions related to natural gas led us in many directions with a vast amount of information, and a challenge was to limit the information to our specific research. Initially, we started out with a cost benefit approach, where we aimed to use its framework for our in-depth investigation. After a period of data collection and assessing the methodological approach, we decided that a complete cost benefit analysis would become too comprehensive. The fact that the method of analysis aim to monetise all relevant impacts (Boardman, 2011), our timeframe would be exceeded if we were to conduct a proper cost benefit analysis. Therefore, the analysis was narrowed down to an investigation of different value chain scenarios while focusing on the externality associated with combustion-related CO_2 emissions, with the objective of internalising these costs. The result of our research must thus be seen together with all other relevant costs, such as investment- and operation costs in order to highlight the best solution.

Regardless of making the thesis more specific, there were still a lot of elements that needed to be excluded from the research to be able to complete the study within our given timeframe: The value chain emissions of CH_4 which has gained a lot of attention with its harmful environmental impact were not included in the analysis as there are still a lot of uncertainty surrounding its actual effects on the environment (Balcombe et. al., 2017). Capacity in existing pipelines and in the mainland electricity grid were in the analysis assumed to be sufficient, which might not be the case in reality. There are difficulties connected to the establishment of an accurate carbon price that will internalise the actual cost of CO_2 emissions as well. Current literature and publications offers a wide range of price estimates corresponding to the two-degree target and valuing the quality of these estimates were challenging. Comparing future carbon prices with abatement costs provided by KlimaKur2020 (Norwegian Environment Agency, 2010) were also not included, although it provides insight on whether the future carbon price is high enough to give incentives for climate efficient solutions.

The research fell within a wide range of topics and touched upon broad research areas such as climate change, energy economics, green logistics, etc., and further refinement regarding the scope of our study were necessary. The research did not aim to analyse the energy markets in Europe, which is why we excluded the emissions concerning the end-consumption in the value chains, where most CO_2 is emitted (Bradbury, Clement, & Down, 2015). The question whether a low carbon society allows natural gas to play a long-term role together with renewable energy sources were also disregarded. The fact that natural gas might provide the low carbon energy mix with flexibility in balancing intraday fluctuations in power demand, were therefor not focused on. The discussion surrounding the effect of carbon pricing on the coal-to-gas switch in Europe were also considered outside the scope of our investigation, although it has an important impact on future gas demand in Europe. Aspects, such as the shale gas story were also ignored, as it did not relate to the Norwegian natural gas value chain.

Finally, with the study being based on future hypothetical value chain scenarios we do not claim that our findings nor results gives an exact presentation of the future situation on the NCS, but rather highlight important elements, possibilities and key factors that will drive the future development of transport infrastructure to accommodate Barents Sea natural gas.

However, the topics we have touched upon during this study opens for a variety of possible additional research on the field, most of which being defined as the limitations of our thesis.

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Appendix

Input used for estimating carbon footprints

Emissions from processing facilities:

Melkøya

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	49 582 625	103 660
Turbine	-	425 378 741	880 110
Engine	28	-	89
Boiler	2	-	7
Other	-	21 012 868	39 119
Total	**30**	**495 974 234**	**1 022 986**

Nyhamna

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	2 403 429	6 262
Turbine	-	-	-
Engine	352	-	1 114
Boiler	-	12 681 289	25 445
Other	-	-	-
Total	**352**	**15 084 718**	**32 821**

Kårstø

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	-	-
Turbine	-	308 422 644	485 814
Engine	-	-	-
Boiler	-	-	-
**Other*	-	-	*1 156 000*
Total		**308 422 644**	**1 641 814**

Note. Source: Norwegian Environment Agency.

Kollsnes

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	8 065 714	18 080
Turbine	-	-	-
Engine	38	-	121
Boiler	-	22 233 907	44 123
Other	-	-	-
Total	**38**	**30 299 621**	**62 324**

Emissions from fields:

Snøhvit

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	-	-
Turbine	-	-	-
Engine	-	-	-
Boiler	-	-	-
Other	-	-	-
Total	**-**	**-**	**-**

Note. Emissions from Snøhvit is part of Melkøya LNG.

Ormen Lange

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	-	-
Turbine	-	-	-
Engine	-	-	-
Boiler	-	-	-
Other	-	-	-
Total	**-**	**-**	**-**

Note. Emissions from Ormen Lange is part of Nyhamna.

Åsgard

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	29 794 771	101 656
Turbine (DLE)	-	306 795 534	733 526
Turbine (SAC)	1 518	64 339 147	158 173
Engine	4 894	-	15 504
Boiler	675	-	2 139
Other	-	-	-
Total	**7 087**	**400 929 452**	**1 010 997**

A.Hansteen

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	-	-
Turbine (DLE)	-	-	-
Turbine (SAC)	-	-	-
Engine	-	-	-
Boiler	-	-	-
Other	-	-	-
Total	**-**	**-**	**218 000**

Note. Source: Impact Assessment Prop. 97 S.

Norne

Source	**Liquid fuel (tonnes)**	**Fuel gas (Sm^3)**	**CO_2 (tonnes)**
Flaring	-	7 151 993	18 362
Turbine (DLE)	-	105 344 925	227 495
Turbine (SAC)	449	55 703 807	121 712
Engine	859	-	2 721
Boiler	-	-	-
Other	-	-	-
Total	**-**	**-**	**218 000**

Production from processing facilities:

Facilities

Processed	**Gas (Sm^3)**
Melkøya	7 077 457 086
Nyhamna	16 791 486 364
Kårstø	26 198 000 000
Kollsnes	43 400 000 000
Total	**93 466 943 450**

Note. The figures are the total volumes processed at each facility.

Production from fields:

Fields

Production	**Oil (Sm^3)**	**Condensate (Sm^3)**	**Gas (Sm^3)**
Snøhvit	-	883 833	7 077 457 086
Ormen Lange	-	1 066 856	16 791 486 364
Åsgard	2 732 371	2 694 254	17 477 768 363
A. Hansteen	-	*189 800*	*5 166 666 667*
Norne	2 071 833	-	2 346 177 573
Total	**4 804 204**	**4 834 743**	**48 859 556 053**

Note. A. Hansteen figures are estimated from the Impact Assessment Prop. 97 S. Also, the gas produced is assumed to be the same volume processed at the respective processing facility.