Norwegian School of Economics
Bergen, Fall 2021

Oil Production in a Changing Climate

An Investigation of Optimal Oil Extraction on the Norwegian Continental Shelf under Current and Potential Climate Policies

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Master thesis, Economics and Business Administration
Majors: Energy, Natural Resources and the Environment
& Economics

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This thesis was written as a part of the Master of Science in Economics and Business Administration at NHH. Please note that neither the institution nor the examiners are responsible – through the approval of this thesis – for the theories and methods used, or results and conclusions drawn in this work.

Acknowledgements

Writing this thesis has been rewarding as well as challenging. We are grateful for the support we have received throughout the semester.

Our supervisors, professors Endre Bjørndal and Mette Bjørndal, have provided constructive feedback and input on our work. We much appreciate your help.

Professor Stein Ivar Steinshamn has guided us in designing our model and shared his knowledge on theory of resource economics.

Anders Toft from the Norwegian Petroleum Directorate provided data on historical operational costs on the Norwegian continental shelf, which was crucial for doing our analysis.

Bjørn Sigve Espeland, together with knowledgeable colleagues from Equinor, has given us weekly insights on how the petroleum industry operates.

Our close ones always give us their support.

Thank you.

Norwegian School of Economics

Bergen, December 2021

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Abstract

This thesis addresses the challenges of being an oil nation in a time where the world needs to combat climate changes. Emissions from fossil fuels are the dominant cause of global warming, and the need for actions to reduce the global combustion is obvious. Despite decades of international climate negotiations, the flow of emissions to the atmosphere continues to grow, and the heat continues towards new heights. Leading environmental economists now suggest restraining the supply of petroleum resources to reach targets related to climate change.

We aim to study the effect today's and potential climate policies have on oil production on the Norwegian continental shelf the next decade. Our results show that the currently announced climate policy does affect the extraction path of oil, given an expected oil price of 552.5 NOK. This is in line with similar research. We also look at the implementation of a production fee on oil. We find that the production fee will reduce resource wealth, and might change the extraction path on existing fields. The latter depends on the size of the fee. The higher estimate of 452.55 NOK per barrel causes 10 out of 11 fields in our sample to stop production. The lower estimatec fee of 25.86 NOK per barrel implies no changes to the extraction paths.

Keywords – petroleum, climate policy, supply side policy, carbon tax, EU ETS, carbon leakage, green paradox, oil extraction, GAMS.

Abbreviations

bbl	Barrel of crude oil
b.o.e.	Barrel of oil equivalents
$\mathbf{CO_2}$	Carbon dioxide
EU ETS	European Union Emission Trading System
GAMS	The General Algebraic Modeling System
GHG	Greenhouse gas
NCS	Norwegian continental shelf
$\mathbf{NO_X}$	Nitrogen oxide
NPV	Net present value
OPEC	Organization of the Petroleum Exporting Countries

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1 Introduction

1.1 Motivation and Purpose

Emissions from the combustion of Norwegian petroleum abroad far exceed emissions inside the country's borders. A debate about Norway's dual role as an oil exporter with billions in revenues, at the same time as being an advocate for ambitious global climate goals has recently erupted. International media such as the New York Times, CNN, and the Financial Times have previously addressed this paradox, calling Norway a hypocrite in the fight against the climate crisis (Milne, 2016; Kottasová, 2017; Sengupta, 2017).

The combustion of fossil fuels is the main cause of global warming. Traditional climate policy is based on interventions that address the demand for, and only indirectly the supply of, fossil fuels (Lazarus and van Asselt, 2018). For decades, policymakers have sought to resolve the climate crisis by measures such as carbon pricing, low-carbon technologies, setting a cap on emissions, and other measures aimed at the demand side. Making it costly to emit follows the 'polluter-pays' principle, which says that the polluters should pay for environmental damage (Kolstad, 2011). By lowering demand, the intention is to reduce the price of fossil fuels, such that producers will leave some reserves untouched in the ground. The demand-side policy also affects extraction[1] through making it costly to release emissions in production.

Despite the efforts, the measures have so far failed to obtain a sustainable use of fossil fuels. Realizing this fact has led policymakers, climate activists, and researchers to look into the potential of supply-side policies (Harstad, 2012; Asheim et al., 2019; Fæhn et al., 2017). Such policies directly attack the extraction of fossil fuels, for example by introducing a fee per unit extracted, setting a cap on extraction, or limiting exploration and licensing of new fields. Recently, the International Energy Agency (IEA) shocked stakeholders by announcing that ending exploration and development of new oil, gas, and coal fields immediately is the only viable climate path (IEA, 2021).

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[1] Economists often prefer the term 'extraction', while the petroleum industry uses the term 'production'. In this thesis, they are used in different contexts but have the same meaning.

By 2030, Norway has committed to cut at least 50 percent of emissions compared to 1990. This target is set to reach the goals of the Paris Agreement, and focuses only on domestic emissions. In this respect, supply-side measures might not be helpful as Norway is a net exporter of petroleum, which means most emissions related to Norwegian petroleum happens elsewhere. Still, though this means deviating from the 'polluter-pays' principle, cutting emissions globally through supply-side measures might be a cost-effective alternative to national cuts (Fæhn et al., 2017; Hoel, 1994),

The main problem of supply-side policies is the threat of carbon leakage. Carbon leakage occurs when a reduction in emissions in one place distorts the market such that it allows for increased emissions elsewhere. It is challenging to measure the size of carbon leakage, and thus the relative cost, of a supply-side policy.

Despite the increasing attention, we find limited research on how climate policies affect the supply-side of fossil fuels in practice. Most research which explores climate policies and oil extraction assumes the theoretical perspective of a social planner (see e.g. Harstad, 2012; Massetti and Sferra, 2010; Hoel, 1994; Rosendahl, 1994; Fæhn et al., 2017). The novelty of this study is that we investigate how profit-maximizing fossil firms react to climate policies. We find how domestic climate policies play out in practice, and the effect on the extraction path of existing fields on the Norwegian continental shelf (NCS). We specifically consider currently announced climate policies focused on the demand side. In addition, we study the effect of a potential supply-side policy, namely a production fee per barrel of oil. In this mission, we attempt to estimate a cost-effective measure of the fee. We estimate alternative measures of the fee, based on contrasting research on carbon leakage by Rystad Energy (2021) and Fæhn et al. (2017). The alternative fees result in different effects on the extraction path.

For the purpose of this study, we have estimated the costs, net present value, and the average emissions per barrel of oil extracted[2]. This insight is important when discussing the future of the oil industry. The variability across fields should be considered in decision-making. Since the model is a simplified version of reality, and the future is hard to predict, the numerical results are only valid as rough estimates, and as a starting point for further research and discussions.

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[2] Hereby referred to as 'carbon intensity'.

1.2 Research Question

We address the following research questions:

Does the current climate policy affect the extraction path of oil on the Norwegian Continental Shelf? How does a production fee affect the extraction path of oil?

Our research approach is to simulate optimal extraction paths under different climate policies. We assume fossil firms as price takers, and look at how the climate policy affect the production costs. We look at a sample of eleven mainly oil-producing fields which have passed peak production. The production fee per barrel of oil is estimated based on research on marginal abatement costs and carbon leakage, and theory on optimal taxes.

1.3 Outline

This thesis is organized in the following way. In chapter 2 we review research literature on climate policies in fossil fuel-producing countries, and optimal oil extraction under such policies. We also introduce a theoretical framework for our model and analysis.

In chapter 3 we present relevant background information for our model and analysis. This includes current climate policies and information about how the petroleum sector operates. We put emphasis on decisions in oil field development and production, as well as the life cycle of an oil field.

In chapter 4 we present our model. We start by explaining how the model relates to theory, and then present the structure of a simple and a more developed model. We also show an expansion of the model, which includes a production fee. In chapter 5 we present the data used in the analysis. We start by presenting our sample of oil fields, and then give reasoning for the input values we have used when running the model.

In chapter 6 we will conduct the analysis and present the results. This chapter gives the answer to our research question. We use the model in two different scenarios, where the first scenario considers the currently announced climate policy, and the second considers the implementation of a production fee. In the second scenario, we also include an estimation of the production fee. We do sensitivity analyses to check the robustness of our results.

In chapter 7, we discuss the implications of our findings. We also discuss the external validity, as well as limitations of our study and suggestions on future research. In chapter 8 we give a conclusion.

2 Literature Review and Theoretical Framework

In this chapter, we take a look at literature relevant for our research question. This includes literature on how climate policies relate to fossil fuel production, as well as literature on optimal oil extraction subject to government intervention.

Next, we introduce theoretical frameworks relevant for our model and analysis. We start by laying a foundation as to why governments should intervene to prevent climate change, and explain the concept of a Pigouvian tax as an optimal tool for intervention. We then look at the framework developed by Hoel (1994), designed to find the optimal combination of supply- and demand-side measures. This lays the theoretical foundation for estimating a production fee. Lastly, we explain the Hotelling rule, which is used to model the optimal extraction of nonrenewable natural resources.

2.1 Literature Review

2.1.1 Climate Policies in a Fossil Fuel Producing Country

The intersection of fossil fuel production and climate policy is the topic of a growing body of research. For example, Bang and Lahn (2019) identify a growing mismatch between significant change in Norwegian climate policy on the one hand, and inertia in petroleum resource management on the other. A different example, Delis et al. (2018) and Fischer and Baron (2015) find that respectively banks and investors price climate policy exposure when they give loans to and invest in fossil fuel firms.

Whereas the traditional focus of environmental policy is on the demand side, a paper by Harstad (2012) investigates the benefits of supply-side policies, including reactions from foreign countries. The study suggests buying abroad fossil fuel reserves and conserving them. A benefit of this approach is that the problem of carbon leakage could be eliminated by choosing to conserve the right reserves. Hoel (1994) shows that a combination of supply-side and demand-side policies is optimal. He mentions a fee on the extraction of petroleum as a specific supply-side policy worth looking into. Muttitt and Kartha

(2020) finds that extraction must be reduced in the near term to reach goals in the Paris Agreement, and suggest that extraction should be phased out faster in diversified, wealthier economies. They point out that rich countries better can absorb transitional impacts.

Lazarus and van Asselt (2018) point out that a supply-side policy is a road less taken due to at least three factors: 1) Greater political attractiveness of demand-side measures, 2) standard GHG emissions accounting rules undervalue supply-side measures, 3) common perceptions of the nature of fuel markets, noting that there seems to be a consensus of more carbon leakage on the supply side. Factor 2) can for example refer to the fact that the Paris Agreement only considers domestic emissions, which can be a problem for supply-side measures in fossil-fuel exporting countries.

Carbon leakage is critical to the effect of climate policies and is the topic in more studies. Fæhn et al. (2017) studies the cost-effective combination of supply-side and demand-side policies in a Norwegian context, in terms of global emissions cuts. The results critically depend on how each policy affects global emissions through international markets. Studies on carbon leakage due to increased consumption include, but are not limited to, (Böhringer et al., 2010), (Rauscher et al., 1997), and (Markusen et al., 1993). Carbon leakage also occurs through supply-side policies aimed at reducing fossil fuel production (Erickson and Lazarus, 2014).

In our thesis, we apply the only studies we have found to investigate carbon leakage in a Norwegian context, Fæhn et al. (2017) and Rystad Energy (2021). There are issues with both of these. Fæhn et al. (2017) might be outdated, as there have been changes in the oil markets since its publication. For example, there has been an increase in the global production of unconventional oil[3], which is associated with more emissions in production, and more flexible production volumes. Rystad Energy (2021) is a report made on behalf of the Norwegian Oil and Gas Association, an employer's association for oil and supplier companies.

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[3] Unconventional oil refers to crude oil which is extracted by non-traditional methods. Such methods include developing oil sands, directional drilling, and hydraulic fracturing ("fracking").

Treaties among multiple countries is suggested as a supply-side approach which limits carbon leakage (Asheim et al., 2019). Similar to how traditional emission regulations work, a climate treaty could oblige countries to keep their extraction levels beneath a set limit, setting a cap on the total supply globally. That is by introducing quotas on extraction.

An important insight from literature is that a shift from demand-side policies to supply-side policies could potentially have implications for long-term developments. If global demand or supply of fossil fuels affect the development of either fossil or renewable technologies, then the different policy approaches will make a difference to the long-run impact of technologies.

Carbon intensive technology may be expensive to build, involving costly initial investments. But, once they are operating, they are relatively inexpensive. Carbon intensive technology systems have a particular tendency to persist over time, due to technological, institutional, and economic factors. We call this phenomenon carbon lock-in, described by Unruh (2002). In essence, carbon lock-in happens when these factors prevent a shift towards zero- and low-carbon systems.

With the threat of carbon lock-in in mind, Mercure et al. (2021) even argue that aggressive climate policies create a comparative advantage in the long term. They show that climate policies give incentives to invest in more future-oriented technologies, which will soon be dominating. The assumed free-riders of climate policies will instead suffer from exposure to stranded assets and lack of investments in decarbonization technologies. The term 'free-riders' refers to countries that benefit from costly climate change mitigation in other countries, without contributing themselves.

Sinn (2008) coined the term 'green paradox', which is the notion that aggressive climate policies on the demand side might, opposite to the intention, lead to an increase in short-term emissions. The green paradox occurs when fossil fuel owners see that future climate policies and support for renewable energy will attack the future profits of their resources, and speed up extraction in the near term as a result. Gerlagh (2010) points out that if the green paradox leads to an increase in oil extraction, we will need to restrict oil supply to counteract this effect, while Hoel (2014) finds that a supply-side policy aimed at higher-cost reserves would prevent a green paradox. Other economists question the existence and relevance of the green paradox (Van der Ploeg and Withagen, 2012; Cairns, 2014; Edenhofer and Kalkuhl, 2011).

2.1.2 Optimal Oil Extraction Under Climate Policies

Optimal oil extraction is subject to national and international policies. While many analysts have forecast the future of oil production (Kontorovich, 2009; Brandt, 2009; Brandt et al., 2010), fewer have looked at oil production forecasts on specific fields in light of climate policies.

Bauer et al. (2013) find that achieving climate protection objectives would dramatically reduce resource rents of fossil fuels, but that conventional oil would still be extracted. Similarly, Massetti and Sferra (2010) looked at socially optimal extraction under climate policy. They find that unconventional oil is not extracted when carbon emissions are constrained. Smulders and Werf (2008) consider high- and low-carbon fossil fuels. They find that with an announced constraint on emissions, it is cost-effective to substitute away from dirty coal to cleaner oil and gas, but to substitute from natural gas to dirtier input oil. This result origins from the fact that productivity matters as well as carbon content, as the economy tries to maximize output per unit of emissions.

Rosendahl (1994) looks at the impact on resource wealth of a global production fee per barrel of oil. He finds that the average resource wealth would decrease by 33–42 percent and that the Norwegian wealth may decrease by 47–68 percent when introducing a tax of $10 per barrel of oil. He points out that these are only rough estimates, due to the simplistic nature of the model used in his paper.

Similar to our thesis, Leighty and Lin (2012) look at the consequences of policies on specific fields, as they model the economically optimal oil production decisions for seven fields on Alaska's North Slope, from the perspective of private owners. Specifically, they simulated the impact of a change in tax policy on the extraction rate. They found that a change in tax rate will not affect the economically optimal oil extraction path, but a change in tax structure may do so. To our knowledge, such a study on specific fields is not done in a Norwegian context.

2.2 Theoretical Framework

2.2.1 Government Intervention

Why is there a need for government intervention when battling climate change? The answer can be explained by basic economic theory. A perfect market needs no government intervention. The demand and supply of a good will create a perfect equilibrium which results in an optimal quantity being sold and purchased, to an optimal price. If more people want the good, the price will increase, which leads to more production. If the cost of production increases, there will be less production due to the same mechanism. The highest possible benefit for society is obtained.

What then makes a market "imperfect" and triggers the need for intervention from policymakers? Examples include monopoly, information asymmetries, factor immobility, and externalities. Emissions from the consumption or production of a good is an example of the latter. While there exist both positive and negative externalities, emissions are obviously negative for society and are therefore a negative externality. This means that there is an additional cost, not paid by the producer nor the buyer, but which the society must pay. We may call this additional cost the *social cost*. This raises the need for policymakers to manipulate the market, to restore perfection. Theoretical optimal interventions include setting a tax on consumption or production of emitting goods, or restricting the total emissions allowed.

The English economist Arthur Cecil Pigou is known for developing the concept of externalities. In his book on the economics of welfare, Pigou argued that negative externalities may be corrected with a tax, and that the tax should equal the social cost of the externality (Pigou, 1920). This type of tax is known as a Pigouvian tax.

2.2.2 Supply Side vs. Demand Side Policies

Fossil fuels are traded between countries. Therefore, it matters whether local climate policies attack the supply or demand side. Hoel (1994) developed a framework that gives the optimal combination of supply- and demand-side policies in a country. Three elements determine the optimal abatement strategy.

First, the cost of a reduction in demand and supply is essential when deciding the optimal abatement strategy. Low-hanging fruits should be picked first, meaning that the cheapest abatement measures should be prioritized. Cost-effective abatement entails that the abatement is done where the marginal abatement cost is the lowest, whether that is on the supply or demand side.

Second, it matters whether the country is a net exporter or net importer of fossil fuels. If the country is a net importer, the price decrease which follows from a demand-side policy is beneficial, while the price increase from a supply-side policy is costly. The opposite is true for a net exporter, where a supply-side policy is the beneficial strategy due to price increase. A higher price would mean more revenue for an oil producer.

Third and last, the size of carbon leakage on the supply- and demand-side is important when deciding the type of policy. Carbon leakage is a phenomenon where climate policies in one country lead to an increase in emissions in another. This happens when local policies make an impact on global markets. Carbon leakage is the most important element to consider, as the consequence of this effect in the most extreme version is that emission reduction in one country entails an even bigger emission increase in another.

Carbon leakage on the demand side happens when a demand-side policy in one country leads to an increase in emissions in a different country. Similarly, carbon leakage on the supply-side happens when a supply-side policy leads to an increase of production of emitting goods elsewhere. For instance, if reduced oil production in Norway leads to a higher world price of oil, the emission reduction may be offset by increased fossil fuel production in other countries.

It gets even more complicated, as manipulations of demand and supply cannot be done in isolation. If a domestic reduction in supply of fossil fuels leads to a global price increase, it will simultaneously lead to a decrease in world demand, and an increase in world supply. The size of carbon leakage is thus closely tied to the price elasticities of world market demand and supply. The price elasticity of demand tells how the quantity consumed changes in case of a price change. Likewise, the price elasticity of supply tells how the quantity produced changes when the price changes. It is the combination of demand and supply price elasticities that determine the net reduction of fossil fuels following a local policy.

The uncertainty of demand and supply price elasticities is a problem when measuring the effect of climate policies. The elasticities are a topic in an article written by the environmental economist Knut Einar Rosendahl, together with Statistics Norway (Fæhn et al., 2017), and a report written by Rystad Energy (2021) for the Norwegian Oil and Gas Association. Both estimate the global net emission reduction from a supply-side policy on oil in Norway, using assumptions of price elasticities. They also consider cross-price elasticities of coal and gas in their respective estimations, as these are considered substitutes for oil. These measures tell how the supply of coal and gas will react to a price change of oil. In addition, they consider differences in emission intensity in extraction across countries.

According to Fæhn et al., a cut in Norwegian oil production will lead to an increase in production elsewhere, but not so much that the entire loss is compensated. The global supply of oil hence decreases, which results in lower emissions in the world. Rystad Energy also concludes that a cut in Norwegian oil production will lead to a lower global supply. But unlike Fæhn et al., this report argues that net oil reduction is very small and that other effects such as low emissions in Norwegian production result in only a marginal effect on global emissions.

Fæhn et al. concludes that a combination of supply- and demand-side measures is optimal in terms of cost-efficiency, indicating the implementation of supply-side measures. In contrast, Rystad Energy claims that the effect of a supply-side policy would be small and that an acceleration of climate policies should be focused on the demand side. Their contrasting conclusions can largely be attributed to different assumptions about how strongly supply and demand react to changes in oil prices in the long term. Summarized, Rystad Energy (2021) finds that the global net emission reduction from a supply-side policy on oil is 2 percent, while Fæhn et al. (2017) finds the same number to be 35 percent of gross emission reduction.

2.2.3 Optimal Nonrenewable Resource Extraction

Why is resource extraction profitable, even in perfectly competitive markets? This particular behavior in markets for nonrenewable resources may be explained by Hotelling's rule, derived by Harold Hotelling in 1931.

Optimal extraction of finite natural resources is a dynamic problem, because the extraction in each period affects the remaining reserves. Hotelling addressed this by making a rule of dynamic efficiency. The rule shows that the marginal revenue of a finite resource should be positive and increasing with the discount rate (Hotelling, 1931).

Formally, one can express the Hotelling's rule as follows:

$$p_t = p_0 e^{rt} \tag{2.1}$$

Where p_t is interpreted as price at time t, p_0 is the initial price (where $t = 0$), and r is the discount rate. In this specification, we assume no marginal costs. In the case of marginal costs, p should rather be interpreted as the marginal profit (marginal cost subtracted from price).

The rule implies that the price needs to rise at the rate of discount to make producers indifferent about temporarily leaving resources in the ground and investing revenues in the financial markets. If the price increases faster than the discount rate, producers would leave their reserves underground until the price has considerably increased. Oppositely, if the price grows at a rate less than the discount rate, producers would sell their oil immediately. This result is used to model optimal extraction. The Hotelling's rule thus provides the extraction path as well as the price path for nonrenewable natural resources.

The rule is dependent on a number of assumptions. It assumes full certainty of quantity in reservoirs, perfectly competitive markets, and no changes in technology. It also assumes that everyone knows the correct discount rate. In the case of petroleum markets, these assumptions do not hold. New reservoirs are constantly discovered, OPEC+[4] controls the oil price to a large degree, and there is a continuous advancement in technology. In

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[4] The Organization of the Petroleum Exporting Countries (OPEC) is an intergovernmental organization of 13 member states. OPEC+ includes its ad hoc alliances with Russia and other countries. Together, they control a large share of the world's oil supply, and thus have great influence on the oil price.

addition, the oil price is victim of world events, most recently seen during the COVID-crisis, which lead to a dramatic fall in oil price. The empirical evidence against the Hotelling's rule is clear. Assuming constant marginal costs, Hotelling's rule suggests a steady increase in price, in stark contrast against the unpredictable, ever-changing historical oil price.

Despite shortcomings, Hotelling's rule reveals an important feature of natural resources, namely the resource rent. The scarcity of natural resources ensures a positive rent even in fully competitive markets.

3 Background

The focus of this chapter is to introduce information relevant to the rest of the paper. We start by introducing international and national frameworks on climate change, as both affect profitability in oil production. The Paris Agreement is making domestic emission cuts the major focus, which impacts the choice of climate policies in Norway. We take a brief look at what actions towards a low emission-society Norway has implemented, as it gives a pointer to the national ambitions and implications for the fossil fuel sector.

The chapter then sheds a light on the importance of the petroleum sector to Norwegian economy and introduce some key elements in the sector relevant for explaining the choices in our model.

3.1 International Framework on Climate Change

Since the burden of global warming is shared unequally, different nations unsurprisingly feel different degrees of responsibility to mitigate emissions. Hence, the problem of free-riding is a threat. We need international agreements to address this problem.

3.1.1 The Paris Agreement

The Paris Agreement of 2015 decentralizes the collective responsibility towards zero-emission, making domestic emission cuts the major focus. In this way, it represents a significant shift in global climate politics (Calmfors and Hassler, 2019). While previously aiming for a common level of ambition, the Paris Agreement allows each country to determine both the form and level of ambition. Countries determine these contributions through Nationally Determined Contributions (NDCs) (Energi og Klima, 2021). Instead of a top-down strategy, making legally binding response of targets, all countries are now obliged to submit national climate plans in a bottom-up voluntary pledge-and-review system (Calmfors and Hassler, 2019). Both the developed and developing countries are included in the mandatory obligations, and the system makes every nation capable to contribute to reduced emissions.

The Paris Agreement Article 2a states that a commitment is made to keep the global average temperature rise “well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” (Paris Agreement, 2015). Despite this commitment, the recent release of the IPCC’s Sixth Assessment Report (2021) illustrates the gap between predicted temperature rise and effective policy response. Based on pledges stated under the Paris Agreement, the best estimate of predicted temperature rise is 3 °C with a likely range of 2.5 °C to 4 °C.

In the most recent conference of climate change summit, the parties agreed to pursue actions to limit warming to 1.5 °C, recognizing that impacts will be less extreme with this level (United Nations, 2021). It was also stated that ineffective subsidies to fossil fuels shall be phased out and that coal power without carbon capture and storage shall be phased down.

3.1.2 EU Emission Trading System

The EU Emission Trading System (EU ETS) is the key in the EU’s policy to combat climate change. All EU climate policy aims to follow the ’polluter-pays’ principle. The intention of the system is to create a market for carbon. The EU ETS is thus a market for emission allowances, where one allowance represents the permission to emit one tonne of CO_2. This means that just as a company must buy the input for production, such as materials and electricity, it must also have enough allowances to cover its emissions. Every year, installations covered by the system must surrender allowances equivalent to their emissions, or face heavy fines (European Commission, 2021a).

The framework was first introduced in 2005, and operates in trading phases. The EU ETS has undergone several revisions to ensure that the emission reductions are aligned with the latest EU emissions reduction targets. This year, the system entered its fourth phase, lasting through 2030 (European Commission, 2021a). Phase 4 represents the need to accelerate cuts in emissions (European Commission, 2021b). The system is made more robust over time by reducing the number of allowances and introducing rules to avoid volatility and carbon leakage. The price as of 2021 is around 50€ per tonne of CO_2, but there is much volatility in the market price for quotas.

The EU ETS follows the ‘cap and trade’ principle, which means that a cap is set on the total amount of emissions each year, and emissions allowances can be traded within the system. This ensures that emissions are cut where it costs the least, which gives an incentive to innovate in low-carbon technologies (European Commission, 2021a). There is a decreasing number of allowances available every year, leading to a decrease in total emissions year by year.

The amount allocated to a company is based on the best performers in the sector, so-called benchmark performers. Relatively high carbon-intensity companies are thus allocated fewer emission allowances than they need, and must buy additional quotas to keep up their emission levels. Alternatively, they can reduce their emission intensity. As the number of allowances is reduced every year, continuous improvement needs to keep up. The price of allowances determines whether a change in production or investing in emission-reducing technology is worth it.

3.2 National Framework on Climate Change

In line with the Paris Agreement, Norway is planning for a transformation towards a low-emission society. In doing so, Norway is pursuing an ambitious climate policy together with the EU, and by 2030 Norway has committed to reduce its GHG emissions by at least 50 percent compared with the reference year 1990 (UNFCCC, 2020). The ultimate goal is to become a zero-emission society by 2050. To reach these goals, Norway has some national specific climate policies. In this section, we introduce the carbon tax, and other national climate policies.

3.2.1 Carbon Tax

As one of the first countries in the world, Norway introduced a carbon tax on the consumption of mineral products, in 1991. The tax aims to limit CO_2 emissions by creating an economic incentive to do so. Consequently, the early implementation may have contributed to the relatively low emissions in Norwegian petroleum production compared to other countries (Calmfors and Hassler, 2019). The revenue from the tax is paid to the government and contributes to the national budget.

Taxation of GHG emissions has been one of the main instruments of Norwegian climate policy, together with the EU ETS, in the later years. Today, the carbon tax mainly covers sectors that are not included in the EU ETS. But the petroleum sector is an exception, as it is covered by both. Other sectors are exempted from the tax.

Depending on the state of the product, the tax is either paid as a fee per liter, kilogram, or cubic meter of the product. This is done for simplicity, and the fee is calculated by estimating the expected emission of consuming the product. The fee should ultimately be equivalent to about 590 NOK per tonne of CO_2 emission. The government plans a gradual increase towards 2,000 NOK per tonne of CO_2 towards 2030 (Regjeringen, 2021c).

3.2.2 Other Climate Policies

The development of new technologies is central to the transition to a low-emission society, and several support schemes are established to accelerate the green shift. The government has established an investment company which aims to make profitable, long-term investments that contribute to reduce GHG emissions (Regjeringen, 2021b). A different example is the NOx-tax, which taxes emissions the same way as the carbon tax. The tax-revenue goes into a fund, supporting measures and technology to reduce future NOx emissions. Further, Norway is a pioneer when it comes to zero- and low-emission solutions on ferries and ships. And when it comes to electrification of the transport sector, Norway is superior. No country in the world has more electric cars per capita, which can be explained by the offensive subsidizing of electric cars.

Norway is also contributing to international work on climate change, which reveals a willingness to contribute to global emission reduction, despite no obligation to do so in the Paris Agreement. Examples include work against deforestation of the rain forest and investments in climate measures in developing countries. In addition, Norway has an important role as a facilitator in negotiations of new international agreements, often as an advocate for more aggressive policies.

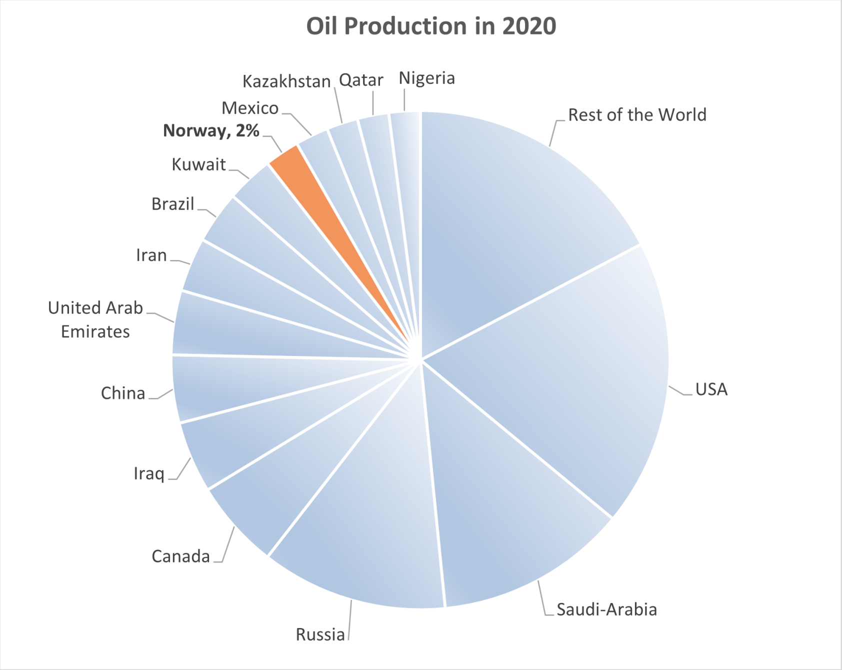
3.3 The Petroleum Sector

3.3.1 Significance of Petroleum in Norway

The petroleum sector is Norway's largest industry and is of great significance in terms of state revenue and value creation (Norwegian Petroleum, 2021f). The combination of enormous value creation from the petroleum sector and the efficient and far-sighted state administration has been the most important driver for welfare development in Norway for the past 40 years (Menon Economics, 2021a).

Almost all oil and gas produced in Norway are exported. This accounts for about half of the Norwegian export value. This makes oil and gas by far Norway's most important export goods. From a global perspective, Norwegian petroleum is of moderate importance and covers about two percent of the world demand for crude oil and three percent of the demand for natural gas (Norwegian Petroleum, 2021b). Figure 3.1 illustrates Norway's share of world oil supply.

Figure 3.1: Oil production across the world, in 2020 (BP plc, 2021).



About half of the assumed recoverable petroleum resources have been extracted so far, according to the Norwegian Oil Ministry (Norwegian Petroleum, 2021h). Since the Norwegian oil adventure started, more than a hundred fields have been developed to produce oil and gas on the NCS. Out of these, 90 fields are still in production, where some have been operating for less than a year, and more fields are currently being developed. There are close to a hundred discoveries that might be developed in the future. Stand-alone developments are planned for the largest discoveries, but most of them are small and can be tied to existing infrastructure (Norwegian Petroleum, 2021a). Producing fields are aging, but some still have substantial remaining reserves. In total, remaining reserves in already developed fields correspond to a quarter of the oil reserves already extracted (Norwegian Petroleum, 2021c).

The petroleum sector pays a tax rate of 78 percent on taxable income, consisting of an ordinary company tax of 22 percent and a resource rent tax of 56 percent. Revenues from petroleum production are placed in the Government Pension Fund, which has investments placed internationally valued to more than 10,000 billion NOK (Norges Bank Investment Management, 2021). This constitutes the largest sovereign wealth fund in the world. Further, the petroleum industry generates great value creation through its employment. Menon Economics (2021b) showed in a report that the total ripple effects of the operators' activities in 2019 amounted to about 180,000 full-time equivalents or 205,000 people employed.

The high tax rate is justified by the extraordinary profitability related to the extraction of petroleum resources and the fact that they extract a scarce natural resource (Norwegian Petroleum, 2021g). Up until this year, the Norwegian government has covered losses connected to exploration, i.e. tax refunds on exploration and cessation. Now, this tax refund system is anticipated to be removed in Spring 2022. Ordinary offshore corporation tax losses will then be carried forward without interest (Ernst & Young, 2021). The change means that tax conditions will be tighter and have a neutral effect on investments.

In 2021, the petroleum sector alone is estimated to form 14 percent of Norway's total revenues (Regjeringen, 2021d). This is clearly the largest economic footprint of any Norwegian industry. While this is a significant share, the relative importance has decreased from 26 percent in 2008 (Langberg, 2020). After the oil crisis in 2014 and increasingly aggressive climate policies, the need to be less dependent on oil and gas production has emerged. A political will for diversification of the Norwegian economy is growing, with a focus on industries more friendly to the environment, such as renewable energy.

National and international political decisions are important for the future of this industry. The development of substitutes within renewable energy likewise. Still, thanks to a substantial amount of recoverable oil and new significant development projects such as Johan Sverdrup, activity on the NCS will likely continue to be crucial to the Norwegian economy in the coming years (Norwegian Petroleum, 2021f).

3.3.2 Emissions and Climate Policies in the Petroleum Sector

GHG emissions might be sorted into three scopes (Greenhouse Gas Protocol, 2021). Scope 1 includes emissions directly related to sources a company owns or controls. Scope 2 includes indirect emissions related to a company's consumption of energy. Scope 3 includes all remaining emissions occurring in the value chain, which the company is indirectly responsible for, in both upstream and downstream activities.

Only a small fraction of total emissions related to petroleum happens in the production (scope 1), and the majority of the emissions in the value chain happens at the end consumer, by combustion of the products (scope 3, category 11). Equinor, the biggest petroleum company in Norway, has an average scope 1 emissions of 8 kilograms of CO_2 per barrel of oil, while the world average is around 17 kilograms per barrel (Equinor, 2021). In comparison, the average emissions from combustion of crude oil is around 430 kilograms of CO_2 per barrel (Statistics Norway, 2021b). Most of the Norwegian petroleum is exported, which means that most emissions happen outside the country's borders.

Scope 1 emissions from petroleum production accounts for about a quarter of the total Norwegian GHG emissions (Norwegian Petroleum, 2021i). Primarily, scope 1 emissions stems from the combustion of fossil fuels in gas turbines, engines, and boilers. The gas turbines are used for oil and gas extraction on the shelf, transport of gas in pipelines, and onshore gas processing. The level of emissions was rising together with production before the turn of the millennium, but has been stable the last 20 years. The pressure to prioritize climate and environment in political decisions is increasing. This translates to increasing costs of emissions, and a pressure to limit the petroleum sector altogether. Therefore, emissions represent a huge issue for actors within the petroleum industry.

The petroleum sector is the only industry in Norway that must pay both the EU ETS and the carbon tax, which in sum represents an increasing cost for the petroleum industry.

The government states that they gradually will more than triple the carbon tax to about 2,000 NOK per tonne of CO_2 in 2030 (Regjeringen, 2021a). However, the government has put a price ceiling telling that the total carbon price imposed on the petroleum sector shall not exceed 2,000 NOK per tonne of CO_2 in the period 2021–2030 (measured in 2020-NOK) (Regjeringen, 2021c).

Emission intensity in Norwegian oil production is already relatively low. According to estimates by Masnadi et al. (2018), Norway is the sixth-lowest emitter when measuring the volume-weighted average crude oil upstream GHG emission intensities, with an intensity below one-third of the countries at the top of the list (Algeria and Venezuela). The low intensity may be explained by regulations imposed on the sector, such as a prohibition to flaring. 'Flaring' is controlled burning of gas, occurring for operational or safety reasons (The Norwegian Environment Agency, 2021).

Higher and more foreseeable carbon prices will make it profitable to cut even more emissions in production. Making the petroleum sector more energy efficient, meaning less emissions for each unit extracted, is a key solution. Electrifying the sector is a way to do this. Several of the fields on the NCS are today fully or partially electrified with power from the power grid on land.

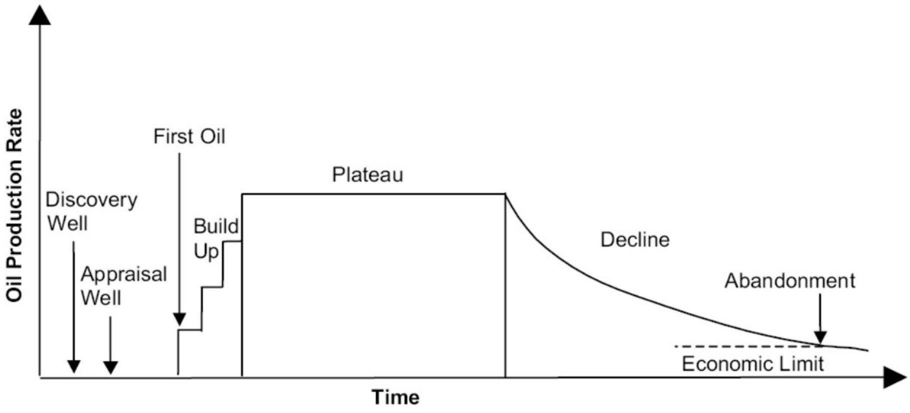
3.3.3 Production Life Cycle of an Oil Field

Exploration, development, and extraction of oil constitute the upstream part of the oil value chain. Decisions considering these activities are subject to long-term profit maximization in a market where the oil companies are price takers (Mohn, 2008).

Exploration licenses are awarded in regulatory licensing rounds, and thereafter it is up to each oil company to decide on a sequence of investments considering development and extraction. Independent of discoveries, there is no further direct intervention by the government, except that large field developments require approval by the Norwegian parliament (Calmfors and Hassler, 2019).

The initial investments of an oil field are enormous, and cover exploration, developing, and building an installation. Once implemented, these can be considered sunk costs, meaning they do not affect decisions of whether to continue production. Once an oil company invests in exploration or development, it aims to recover capital expenditures as fast as possible. Capital recovery is strongly related to the speed of production, and any delay to either development or production means a reduction in NPVs. The production life cycle of an oil field from discovery to abandonment can be described by different phases, as illustrated by Figure 3.2.

Figure 3.2: Oil production life cycle (Höök, 2009).



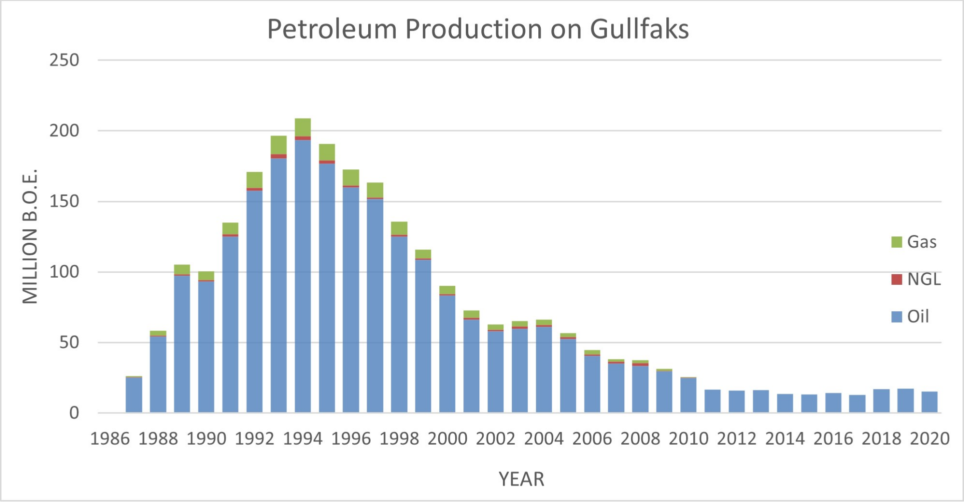
The scope of the analysis is limited to the extraction part of the upstream activities. The initial phase following discovery and development is characterized by a gradual build-up of production. The field then reaches its peak, and enters the plateau production phase. In this phase, the pressure in the reservoir is so high that there are no problems extracting the oil, from hundreds or thousands of meters below the ground.

As the oil reserves are decreasing, the pressure gets lower. This complicates the extraction, as more power is needed to pull the oil to the surface. Gas or water might be pumped into the reservoirs to increase pressure. The energy demand of production is increasing. This translates to increasing costs, as well as increasing carbon intensity (Masnadi et al., 2018). We can call this phase the decline phase, or alternatively the tail phase. Fields in this phase can be referred to as mature fields.

Costs of an oil field in the phases involving extraction can be divided into operational costs and investments. The operational costs on a platform are mainly constituted by the maintenance of platforms and wells, in addition to daily operation and maintenance of machines (Norwegian Petroleum, 2021e). The investments are mainly due to drilling of new wells, investments to prolong lifetime, and to reduce carbon intensity. The costs vary extensively among the fields and depend on different conditions such as the location, age, and the size of the installation.

Figure 3.3 shows the yearly production volume at the field Gullfaks, as an example of how the production volume varies over time. Gullfaks is currently in the tail phase of production.

Figure 3.3: Production on Gullfaks, a mature field operated by Equinor (Norwegian Petroleum, 2021d).



At a certain point, the costs of extraction exceed the gains. At this point, the remaining reserves are deemed unworthy of extraction, and the field is abandoned. The time of abandonment depends on the economic limit, which is determined by marginal costs, long-term expected oil price, and taxes. Alternatively, abandonment happens when there is no recoverable oil left in the reservoir.

The dismantling process of a field starts once an installation is no longer in use. The government requires the area to be cleared and the installation fully or partly removed, in addition to providing a detailed description of the process in a dismantling plan. When deciding to end production at a field, all profitable and recoverable oil and gas resources must have been produced. It is difficult to estimate when a field will shut down. In many cases, investments in new tie-ins have prolonged production at fields, in addition to improved technology which has extended lifetimes beyond original estimates. If a field functions as a host for other installations, the lifetime may also be expanded.

4 Model

A model to optimize oil production on a specific field is constructed, from the perspective of a profit-maximizing petroleum company. The model is used for finding the optimal extraction path under climate policies.

We will first describe how Hotellings' rule applies to our model. Next, we describe the model and its structure. We start by presenting a simple version of the model, followed by the model used in our analysis. The main difference between the two versions is that dismantling time is given in the simple version, while it is derived from the model in the more complex version. The purpose of presenting two versions of the model is that the simple version provides an easier intuition, while the complex version is more practical to use. We also include an expansion of the model to include a production fee.

4.1 Hotelling's rule: An Alternative Approach

Hotelling's rule is often used to model the optimal extraction of non-renewable resources. The Hotelling's rule states that the marginal profit from extracting a resource should equal the marginal profit of letting the resource stay in the ground (Hotelling, 1931). This rule makes it possible to model extraction paths under different scenarios, such as different discount rates.

The model is based on dynamic optimization and Hotelling's rule in that resources are left in the ground when the shadow price is 0. However, certain alterations are done to the traditional use of the rule. We model optimal oil extraction on specific fields, as opposed to total extraction. The assumption of known reservoirs is more reasonable when looking at specific mature fields, as opposed to the global oil reserves. We also introduce a restriction on extraction capacity and apply an exogenous oil price. The aim of these modifications is to gain more realistic results.

4.2 A Simple Model With Given Time Horizon

The model should be applicable to the real world, though conditions and factors of minor relevance should be left out to avoid noise and complexity. The model must therefore include the most relevant decision factors in oil production. We can assume that those are factors that affect the present value of production, such as costs, the oil price, and the carbon price. Taxes can be excluded, as it has a neutral effect on production decisions. The production volume in each time period is constrained by the extraction capacity on the field. Further, the company must pay dismantling costs when the production is stopped on the field.

For simplicity, we use an exogenous oil price, though we will test for different levels of the price in our analysis. We also assume constant costs and carbon intensity. The dismantling costs are assumed to take place the year after ending production.

The model is constructed by the following parameters and variables, where t denotes years:

x_t	Decision variable: Quantity in barrels produced at time t
T	Dismantling time, total periods
p_t	Oil price at time t
A	Recoverable oil at $t = 0$
M	Maximum extraction capacity in each period
v_t	Carbon price (tax + price of quota) at time t
c	Unit cost of production
ρ	Discount factor: $\frac{1}{1+r}$ where r is the discount rate
i	Carbon intensity (emissions per unit of oil)
w	Fixed costs in each period
b	Dismantling costs

The objective is to maximize NPV before tax, defined by the objective function 4.1:

$$\max_{x_t} \sum_{t=1}^{T-1} \rho^t [(p_t - c - v_t i)x_t - w] - \rho^T b \tag{4.1}$$

The value of T is indirectly determined by choosing the T which gives the maximum value.

The objective function 4.1 must be maximized subject to the following constraints:

$$\sum_{t=1}^{T-1} x_t \leq A \tag{4.2}$$

Equation 4.2 shows that the total extraction cannot exceed what is available in the reservoir.

$$x_t \leq M \qquad t = 1, ..., T \tag{4.3}$$

Equation 4.3 shows that the extraction at time t cannot exceed the maximum extraction capacity.

$$x_t \geq 0 \qquad t = 1, ..., T \tag{4.4}$$

Equation 4.4 shows that the extraction cannot be negative.

4.3 A Model With Free Time Horizon

Here we introduce a more developed version of the model. We consider an infinite time horizon, where the dismantling time is determined by the decision variables in the model.

In order to obtain dismantling time directly from the model, we introduce additional, binary decision variables:

y_t^1	Production decision. 1 if producing in year t, 0 if not.
y_t^2	Dismantling decision. 1 if dismantling in year t, 0 if not.

The objective is still to maximize NPV of extraction, defined by the rewritten objective function 4.5:

$$\max_{x_t, y_t^1, y_t^2} \sum_{t=1}^{T} \rho^t [(p_t - c - v_t i)x_t - w y_t^1 - b y_t^2] \tag{4.5}$$

T is set to a value well above the expected time of dismantling.

The constraints already described apply, but we make an adjustment to Equation 4.3:

$$x_t \leq M y_t^1 \qquad t = 1, ..., T \tag{4.6}$$

Equation 4.6 forces fixed costs if production happens, and restricts extraction to the maximum extraction capacity.

To force dismantling, we introduce an additional constraint:

$$y_t^1 - y_{t+1}^1 \leq y_{t+1}^2 \qquad t = 1, ..., T \tag{4.7}$$

Equation 4.7 shows that dismantling must happen the period after the production stops. As dismantling entails a cost, the company will not dismantle unless it is forced.

4.4 Expanding the Model: Including Production Fee

We expand the model to include a production fee. This is simply done by adding a parameter to the model:

f	Production fee

The objective is still to maximize NPV of extraction, defined by the rewritten objective function 4.8:

$$\max_{x_t, y_t^1, y_t^2} \sum_{t=1}^{T} \rho^t [(p_t - c - v_t i - f)x_t - w y_t^1 - b y_t^2] \tag{4.8}$$

5 Data

In this section, we describe the data used in our analysis. The data is obtained from three main sources. From the Norwegian Petroleum Directorate, we received historical operational costs on all Norwegian fields from 1994 to 2019 (Anders Toft, personal communication, November 2, 2021). From the public Norwegian Petroleum Directorate web page, we collected data on future investments, production volume, initial reserves, and recoverable oil (Norwegian Petroleum, 2021c). From the Norwegian Environment Agency, we retrieved data on historical CO_2 emissions (Norwegian Environment Agency, 2021). Equinor has provided data on dismantling costs for a sample of anonymized fields from Equinor. Further, we base the oil price on estimates in Equinor's annual report (Equinor, 2021b).

In the following subsections, we describe the sample of fields, the data, and how we find the model input values to be used in the analysis.

5.1 Sample of Fields

Equinor has been the source for understanding costs and other important measures. We therefore choose to only look at fields operated by Equinor, to avoid problems of differences across companies.

Including both oil and gas in our model would complicate the analysis. We address this problem by focusing only on oil production. There are more reasons for leaving out gas production from our analysis. As Holtsmark (2019) remarks, Norwegian gas exports are mainly used in the European market, and thereby are covered by the EU ETS. Reducing gas production can therefore lead to small or negligible effects on global emissions. Moreover, coal is the main substitute for gas, which builds on the fact that reducing gas in Norway might not reduce emissions globally. Coal emits more than both oil and gas compared to energy output.

Our model uses constant costs, extraction capacity and carbon intensity. For fields in the build-up or peak production, we would expect sudden changes to these parameters as the field matures. Therefore, we choose to only look at fields which have passed the peak production phase. We base the parameters on periods included in the tail phase of production.

The requirements for the fields in our sample are summarized in the following:

- At least 90 percent share of oil
- Remaining reserves are less than 30 percent of initial reserves
- Located on the Norwegian continental shelf
- Operated by Equinor

These requirements capture that we only want to look at oil production, mature fields, and fields operated by Equinor in Norwegian territory. Eleven fields meet these requirements: Grane, Gullfaks, Oseberg Øst, Skuld, Snorre, Statfjord Nord, Svalin, Sygna, Tordis, Urd, and Vigdis. These are mostly fields that have been producing since between late 80s and early 2000s. The exceptions are Skuld and Svalin, which started producing in 2013 and 2014 respectively.

Though the carbon intensity and costs in general will increase as a field gets older and demands more energy for extraction (Masnadi and Brandt, 2017), we have not seen this as a general trend for the fields in our sample, perhaps due to technology improvements. Therefore, it is reasonable to assume a stable carbon intensity and inputs of costs for our fields, based on an average of the last 5 years. It should be noted that this assumption is especially problematic for Gullfaks, Snorre, and their connected fields. The conditions on these fields will change in the coming years due to the installation of Hywind Tampen, a floating wind park that will provide power for production.

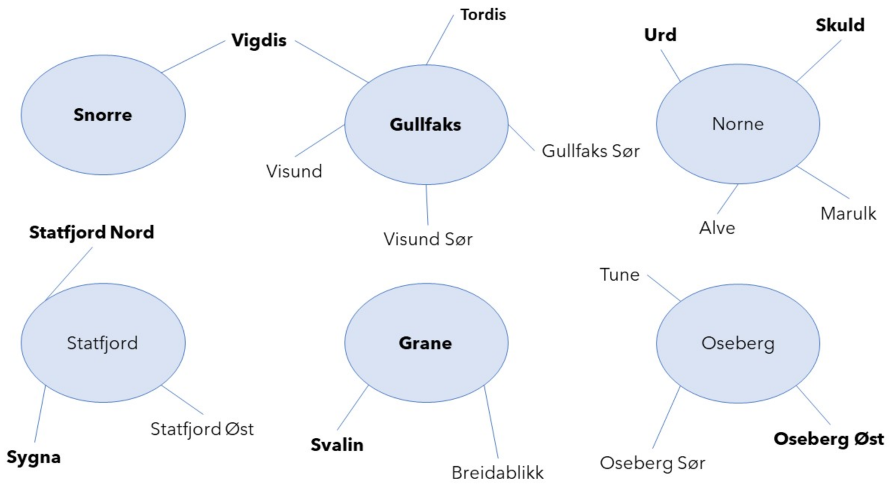
The oil fields have very different costs – but common for all fields is that they have relatively high carbon intensities compared to newer assets. The intensities on the fields examined are all above the reported average of 8 kg CO_2/barrel (Equinor, 2021). We believe that the focus on mature fields provides a suitable benchmark for further analysis of larger, less costly and less carbon-intensive fields. Table 5.1 summarizes descriptive statistics of the fields.

Table 5.1: Summary statistics for the fields included in the sample. Remaining reserves refers to remaining recoverable oil (Norwegian Petroleum, 2021c).

Field	Production start	Initial reserves (in million bbl)	Remaining reserves (in million bbl)
Grane	2003	949.13	144.04
Gullfaks	1986	2,615.61	91.20
Oseberg Øst	1999	158.13	11.95
Skuld	2013	73.02	9.43
Snorre	1992	2,052.68	537.15
Statfjord Nord	1995	301.66	28.30
Svalin	2014	61.07	18.24
Sygna	2000	1.63	5.03
Tordis	1994	476.33	30.82
Urd	2005	56.17	8.18
Vigdis	1997	500.16	67.30

Equinor fields are organized in clusters. Oil from a field (a third party) could be transported to a host field to be processed or stored. Figure 5.1 illustrates the cluster of fields in our sample. Though we analyze the fields in isolation, this connection between the fields is necessary to address when estimating input values. For example, Gullfaks is the host of productions from five different fields. The extraction capacity in our analysis only refers to oil originating from that field. We do not consider where the extracted oil is processed.

Figure 5.1: Clusters of fields. The fields included in our sample are marked by bold font.



5.2 Model Input Values

5.2.1 Summary of Input Values

Table 5.2 lists the input variables and their chosen values. Table 5.3 lists the field-specific values. We thoroughly explain the calculations of the input values in the next subsections.

Table 5.2: Summary of input values.

Variable	Description	Value
p_t	Oil price	552.5 NOK
A	Initial reserves	5,000,000 - 537,000,000 bbl[5]
M	Extraction capacity	900,000 - 31,000,000 bbl
v_t	Carbon price	1,000 - 2,000 NOK
c	Unit cost	3.22 - 157.61 NOK
r	Discount rate	8 %
i	Carbon intensity	0.91 - 2.87 kg/b.o.e[6].
w	Fixed costs	0 - 22,193,000,000 NOK
b	Dismantling costs	1,900,000,000 NOK

Table 5.3: Field specific input values.

Field	Carbon intensity (tonnes CO_2/bbl)	Unit Cost (NOK)	Fixed cost (million NOK)	Extraction capacity (bbl)	Total reserves (bbl)
Grane	0.0287	20.47	1,803.77	29,880,181	144,036,420
Gullfaks	0.0091	58.04	3,696.34	15,190,341	91,202,100
Oseberg Øst	0.0178	144.92	416.66	3,014,145	11,950,620
Skuld	0.0158	27.99	130.09	1,723,810	9,434,700
Snorre	0.0122	71.88	2,855.30	30,979,262	537,148,920
Statfjord Nord	0.0248	36.58	149.51	2,484,833	28,304,100
Svalin	0.0287	3.22	0.00	6,310,781	18,240,420
Sygna	0.0248	157.61	29.13	927,828	5,031,840
Tordis	0.0091	48.55	367.81	5,152,638	30,820,020
Urd	0.0158	38.33	191.20	2,035,676	8,176,740
Vigdis	0.0122	75.32	954.11	10,371,866	67,300,860

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[5] bbl = barrels of crude oil

[6] b.o.e. = barrels of oil equivalents.

5.2.2 Oil Price

An element of significant uncertainty is the future price of oil. Oil price forecasts tend to differ significantly over time, and the price is highly dependent on world events. In 2020, the world hit an oil crisis and prices fell dramatically due to an oil price war in OPEC and the COVID-19 crisis (Hansen, 2020). From January to April the same year, the oil price fell from approximately $70 a barrel to about $20 a barrel (DN Investor, 2021). In 2021, the oil price has steadily climbed back to previous heights, hovering around $80 as the year is approaching the end.

In our main analysis, we use the long-term expected oil price by Equinor. Due to potential long-term effects on demand of the ongoing Covid-19 pandemic and expected development of the drivers for commodity prices and exchange rates, Equinor downgraded its long-term price assumptions last year. Equinor (2021b) assumes the oil price to be $65 a barrel for 2025, with an increase towards 2030. After 2030, they expect a gradual increase towards an estimate of $64 a barrel in 2040. In 2050 the oil price is expected to be under $60 a barrel.

Based on Equinor's assumptions, we use an expected oil price of $65 as the main oil price estimate, in all time periods.

The annual report further announces new assumptions about long-term exchange rates from 2023 onwards, which we use in our analysis. This exchange rate of NOK/USD is 8.5, a conclusion that is supported by the historical 5-year average and spot prices in the foreign exchange market, as well as expected lower oil prices and increased uncertainty in the market. The price we use as our main estimate is then 552.5 NOK per barrel.

5.2.3 Unit Costs and Fixed costs

Conditions such as age, size, and location mean that the unit costs and fixed costs vary for each field. Data from The Norwegian Petroleum Directorate has allowed us to make field-specific calculations of costs. The costs are converted to 2020-NOK, based on the consumer price index published by Statistics Norway (2021a).

Operational costs on a platform mainly consist of daily operation and maintenance of the installation wells, and machines. Therefore, the operational costs represent the unit costs of production in the model. We use a constant unit cost, which is found by dividing operational costs in the last five years on production volume. For fields that also produce gas, we use the share of costs which corresponds to the share of oil.

We assume that investments must be done regularly to maintain production. Therefore, fixed costs are based on the company forecast of future investments, which includes investments related to the production of reserves (Anders Toft, personal communication, November 2, 2021). We estimate a fixed investment cost based on the total investment forecast divided by the recoverable oil. Multiplying this number by the average production in a year gives us an average yearly fixed cost to maintain production.

5.2.4 Extraction Capacity and Recoverable Oil

We retrieved data from The Norwegian Petroleum Directorate (2021) on yearly extraction capacity and recoverable oil. All the fields in this analysis are in the tail phase of production, with relatively stable production volume in the last few years. The yearly extraction capacity for each year is based on the last 5-10 years, where the choice of years is done by visual inspection of when the flattening out happened.

5.2.5 Carbon Intensity

By using data on emissions from Norwegian Environment Agency (2020), we have calculated the carbon intensity for each field by dividing the total amount of CO_2 emissions per year on the yearly production of oil equivalents. Connected fields are assumed to have the same intensity, based on the total of emissions originating from the cluster of fields. This assumption, also applied by Equinor in internal accounting, is chosen because some fields have additional emissions related to the processing of oil from connected fields (Equinor employee, personal communication, November 15, 2021). Notice that Vigdis sends oil for production to both Snorre and Gullfaks. To calculate carbon intensity for the two different clusters, we divide the production from Vigdis into two equal parts, as a simplification in this case.

5.2.6 Dismantling Costs

The costs of dismantling are uncertain and will vary from field to field. Installation size and equipment vary across fields, and distances from land are also different, which all impact the total costs. The costs further depend on the general cost development in the industry, the availability of assets, and the capacity of services connected to the dismantling process. As the industry gains more experience, one can expect higher efficiency and thus also a lower cost level. One can also expect that larger platform units on the NCS will provide certain «economies of scale» to the dismantling process.

All these circumstances make it difficult to make an accurate estimate of dismantling a field. Rystad Energy (2020) estimates that dismantling costs the next 5 years for assets in the North Sea will be about 144.5 billion NOK. Around 115 assets are closing down during these years, which gives an average dismantling cost of about 1.3 billion NOK. Another estimate is based on a data set received from Equinor with an overview of dismantling costs the next 25 years for nine anonymous installations. This gives us a higher estimate than that of Rystad, with an estimated average cost of 1.9 billion NOK. In our model, we base the dismantling cost on Equinor's data set.

5.2.7 Discount Rate

Equinor uses a discount rate of 8 percent (Equinor employee, personal conversation, November 15, 2021). As our sample only includes fields operated by Equinor, we therefore apply a discount rate of 8 percent. It can be noted that Equinor thus has a higher discount rate than the recommended discount rate of 7 percent for income and expense flows in the petroleum industry (Ministry of Petroleum and Energy and Ministry of Labour and Social Affairs, 2017).

5.2.8 Carbon Price

The carbon price is the sum of the carbon tax and the price of quotas in the EU ETS. Both the carbon tax and the price of quotas is scheduled to increase in the near future. As the petroleum sector must pay both taxes and quotas, the government has announced that the total carbon price will not exceed 2,000 NOK (in 2020-kroners) before 2030. We therefore model the carbon price as steadily increasing each period to reach 2,000 NOK by year 2030. Assuming a carbon price of 1,000 NOK in 2020, we therefore assume an increase of 100 kroner per year to reach 2,000 NOK in 2030.

6 Analysis and Results

In this chapter, we seek to answer the research questions: *Does the current climate policy affect the extraction path of oil on the Norwegian continental shelf? How does a production fee affect the extraction path of oil?* In this mission, we look at two different scenarios. The first scenario considers the currently announced climate policy. The second scenario considers the hypothetical implementation of a production fee. We find the results by using the model and data described in the previous sections. Specifically, we optimize the NPV of each field in our sample to find the aggregated extraction path. The dynamic optimization problem is solved in GAMS (The General Algebraic Modeling System), by using a mixed-integer programming (MIP) solver.

For the analysis, we are situated in the year 2020 and consider the year 2021 and beyond. While the focus of this thesis is the climate policies announced up to year 2030, we include results beyond this period. That means that we assume a similar development in the carbon price after year 2030. The values in NOK are in real 2020-kroner.

6.1 Scenario 1: Current Climate Policy

In scenario 1, our benchmark scenario, we consider the currently announced climate policy up to 2030. The climate policy relevant for the petroleum sector is the combination of EU ETS emission quotas and the Norwegian tax on emissions. We call the sum of these 'carbon price', which is paid per tonne of CO_2 emitted in production. We will look at the extraction path and NPV for each field in our sample under this policy. We also do a sensitivity analysis, to find the robustness of our results.

We study the current extraction path of our sample in terms of production volume and time of dismantling. We then compare this to a scenario with no climate policy to find the effect of the climate policy. The currently announced climate policy entails a gradually increasing input value of the carbon price. The input for v_t in the model starts at 1,000 in year 1 and 1,100 in year 2, etc., reaching 2,000 NOK per tonne of CO_2 by 2030.

6.1.1 Results

Figure 6.1 illustrates the aggregated extraction path under the currently announced climate policy. For comparison, we run the model with a carbon price equal to zero in all years. We find that the extraction path is exactly the same. These results indicate the following answer to our research question: The current climate policy does not affect the extraction path of oil.

Figure 6.1: Aggregated extraction path for the sample of fields, with the currently announced climate policy.

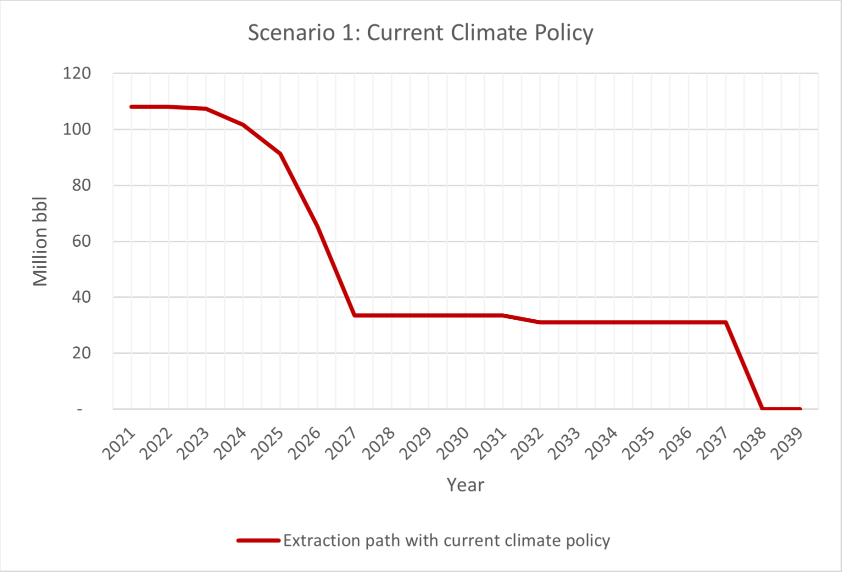


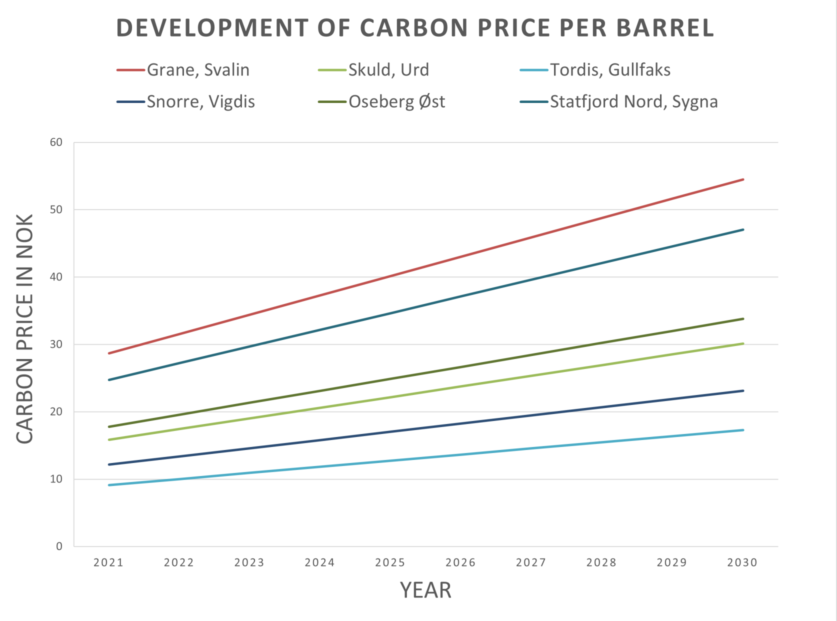
Table 6.1 summarizes the years of dismantling, NPV, and total extraction for each field. The optimized NPV varies greatly across fields, mostly due to different volumes of oil in the reservoir. For comparison, we also include the hypothetical NPV under no climate policies. The difference between these measures is thus what is spent on the carbon tax and EU ETS emission quotas. Though the carbon price does not affect the quantity extracted and the time of dismantling, it affects and reduces the NPV on each field, as it increases the cost of production. The reduction in NPV varies from 0.12 to 5.57 billion NOK for the various fields. Reducing emissions could increase the NPV significantly. This means that business as usual entails a great opportunity cost.

Table 6.1: Optimal year of dismantling, NPV and total extraction on each field.

Field	Dismantling	NPV Scenario 1 (billion NOK)	NPV carbon price = 0 (billion NOK)	Total extraction (million bbl)
Grane	2026	49.22	53.13	144.04
Gullfaks	2027	15.74	16.53	91.14
Oseberg Øst	2025	1.16	1.36	11.95
Skuld	2027	2.03	2.17	9.43
Snorre	2038	103.72	109.29	526.65
Statfjord Nord	2032	5.52	6.14	27.33
Svalin	2024	6.75	7.24	18.24
Sygna	2027	0.20	0.32	5.03
Tordis	2027	8.12	8.39	30.82
Urd	2025	1.42	1.54	8.14
Vigdis	2027	18.78	19.5	62.23

We also check exactly how much the carbon price amounts to per barrel of oil. Figure 6.2 illustrates the carbon price paths for the different fields. The differences across fields are due to different carbon intensities. The carbon price per barrel does not exceed 30 NOK in year 2021 and in 2030 these costs vary from 14 to 47 NOK, though most fields end production before this point. In comparison, the profit per barrel[7] is well above 200 NOK for all fields in our sample in all production years up to 2030.

Figure 6.2: Carbon price paths up to 2030.



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[7] We find the profit per barrel by a simple calculation: $\frac{(p_t - c)x_t - w}{x_t}$

6.1.2 Sensitivity Analysis

There is great uncertainty about several of the estimated parameters. In this section, we therefore conduct a sensitivity analysis on different parameters to see how robust the extraction path is for variations in each of these.

Oil Price

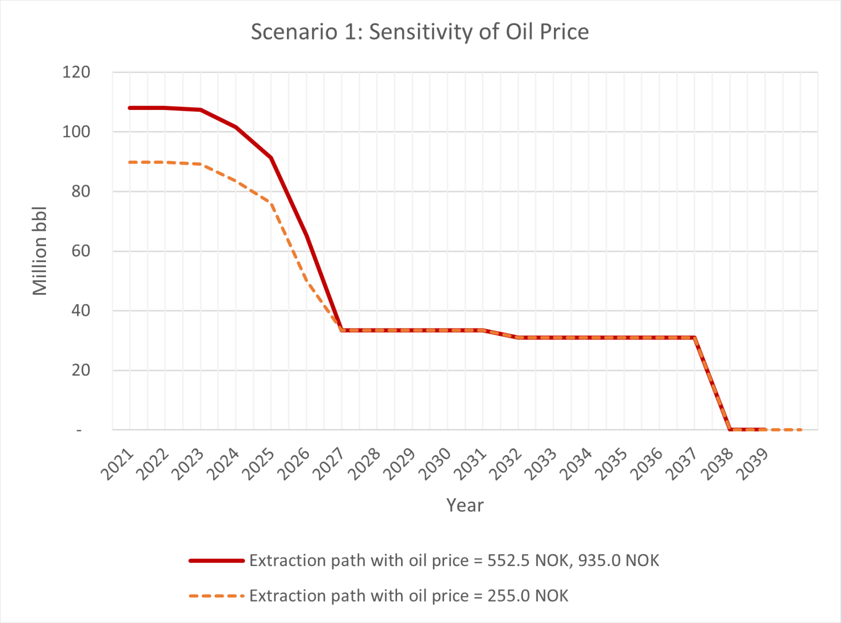
The expected oil price is perhaps the biggest source of uncertainty in our model. As the world oil price is stated in USD, the oil price in NOK is victim of two volatile parameters; the oil price and the USD/NOK exchange rate. The exchange rate and the oil price can be in disfavor for oil producers simultaneously. We choose to capture this uncertainty by keeping the exchange rate constant, while checking for large changes in the expected oil price in USD values. Therefore, we run the model with uttermost values of oil price predictions for the future, i) \$30 and ii) \$110.

i) The low price scenario is based on an oil price of \$30 per barrel and an exchange rate of 8.5 USD/NOK. This gives an oil price of 255 NOK. Senior vice president for strategy in Equinor, Philippe Mathieu, stated that they expect good value creation even if the price goes down to \$30 per barrel (Equinor, 2021a). We would like to see how this holds for our sample of fields, as a long-term low oil price expectancy.

ii) The high price scenario is based on an oil price of \$110, while keeping the exchange rate of 8.5 USD/NOK. This gives an oil price of 935 NOK.

There is no change in the extraction path with the oil price of 935 NOK. With the low oil price of 255 NOK per barrel, Gullfaks and Oseberg Øst will change their extraction paths, summarized by Table 6.2. Both fields end production immediately with this low oil price expectation. The extraction at the other fields remains the same. Figure 6.3 illustrates the change in the aggregated extraction path.

Figure 6.3: Aggregated extraction paths with different oil prices.



This implicates that there is an oil price somewhere above 255 NOK where the carbon price makes the marginal difference to the profit, causing a change in the extraction paths of only two fields.

Table 6.2: Fields where there has been a change in optimal year of dismantling and total extraction, with an oil price of 255 NOK per barrel. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Gullfaks	2021(-6)	0.00(-91.14)
Oseberg Øst	2021(-4)	0.00(-11.95)

Carbon Price

It is possible that policymakers will deviate from the announced climate policy. As we found that the currently announced climate policy has no effect on the extraction path, we check if even more aggressive policies will make a difference. We test for two different carbon price paths, significantly more aggressive than the current carbon price path:

i) yearly increase of 500 NOK. i.e, carbon price is 1,000 in year 1, 1,500 in year 2, etc.
ii) yearly increase of 1,000 NOK. i.e, carbon price is 1,000 in year 1, 2,000 in year 2, etc.

Neither causes a change in the aggregated extraction path.

Fixed Costs and Unit Costs

Our model uses constant fixed costs and unit costs. To see how robust the results are to these measures, we look at extraction paths in different fixed and unit costs scenarios simultaneously. We test for:

i) Fixed and unit costs increase by 25 %

ii) Fixed and unit costs decrease by 25 %

For i) we get no change in extraction paths. For ii) we get only a very slight change in the extraction path, summarized by Table 6.3.

Table 6.3: Fields where there has been a change in optimal year of dismantling and total extraction with a 25 % decrease in costs. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Statfjord Nord	2033(+1)	28.30(+0.97)
Urd	2026(+1)	8.18(+0.04)

Dismantling Costs

Our results are based on a calculation of dismantling costs that is highly uncertain, and that will likely differ on the various fields. It is also possible that the government will subsidize dismantling. Due to this uncertainty, we test for:

i) 25 % increase in dismantling costs

ii) 25 % decrease in dismantling costs

iii) no dismantling costs

For i) and iii) we observe changes in the extraction path. For ii) there is no change.

An increase in the dismantling costs causes adjustments to extraction paths on Statfjord Nord and Urd. The intuition is that higher dismantling costs make it profitable to extend the extraction path, as it would postpone and discount the costs. Table 6.4 shows the changes in the extraction path for the impacted fields.

Table 6.4: Fields where there has been a change in optimal year of dismantling and total extraction, with a 25 % increase in dismantling costs. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Statfjord Nord	2033(+1)	28.30(+0.97)
Urd	2026(+1)	8.18(+0.04)

Further, we observe that when the dismantling costs are zero, Skuld and Sygna will extract less and dismantle earlier, see Table 6.5. This is the same result as when there was a decrease in costs, see Table 6.3. The intuition is that fields that profited from extending the extraction path due to high dismantling costs have lost this incentive when the dismantling costs are zero.

Table 6.5: Fields where there has been a change in optimal year of dismantling and total extraction when the dismantling costs are set to zero. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Skuld	2026(-1)	8.61(-0.82)
Sygna	2026(-1)	4.64(-0.39)

These results reveal that dismantling costs might cause oil companies to extend production time.

Recoverable Oil

It is difficult to estimate when a producing field will shut down, and normally installations produce for a longer period and extract more oil than planned at the stage of development. This could be due to both new discoveries at a field, or technology improvements making more oil in a reserve recoverable. Therefore, in Figure 6.4 we show how the time of dismantling would change when there is 25 percent more recoverable oil at a field. We also test if this makes a difference to the conclusion of no effect from current climate policies. We test for:

i) 25 % increase of A
ii) 25 % increase of A, no climate policies

The result is that i) and ii) give the same extraction path. All fields would increase extraction. See Figure 6.4 for the aggregated extraction path with a 25 percent increase in recoverable oil.

Figure 6.4: Aggregated extraction paths with current policies, two different recoverable oil scenarios.

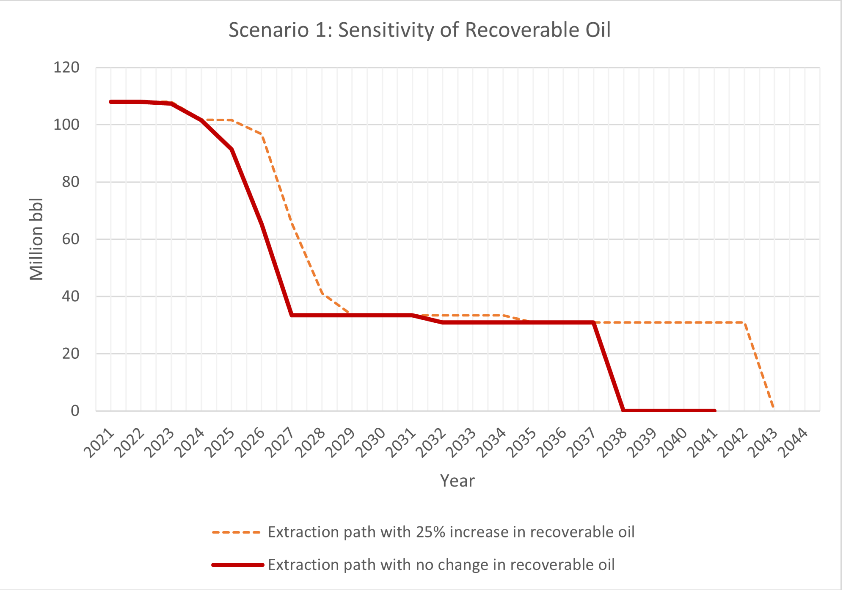


Table 6.6 shows the change in extraction path when recoverable oil has increased by 25 percent.

Table 6.6: Optimal year of dismantling, with a 25 % increase of recoverable oil in the reservoir. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Grane	2028(+2)	179.28(+35.24)
Gullfaks	2030(+3)	114.00(+22.86)
Oseberg Øst	2027(+2)	14.94(+2.99)
Skuld	2029(+2)	11.79(+2.36)
Snorre	2044(+6)	671.44(+144.79)
Statfjord Nord	2036(+4)	34.79(+7.46)
Svalin	2025(+1)	18.93(+0.69)
Sygna	2028(+1)	5.57(+0.54)
Tordis	2029(+2)	36.07(+5.25)
Urd	2027(+2)	10.18(+2.04)
Vigdis	2029(+2)	72.60(+10.37)

6.2 Scenario 2: Production Fee per Barrel of Oil

In scenario 2, we investigate the effect of a hypothetical policy that directly targets the supply side, in addition to the current climate policy. We specifically consider a domestic production fee that must be paid per barrel of oil, in addition to the carbon price described in the previous scenario. We thus use scenario 1 as a benchmark and build on the results.

A fee on the extraction of oil is suggested by Holtsmark (2019) as an effective tool on production. She argues that a fee on extraction is cost-effective and easy to implement. As opposed to limiting exploration and new licensing, it also allows for differentiation between oil and gas. This is useful as oil is considered worse for the environment than gas. Such a policy where the producer is made responsible for scope 3 emissions entails a shift from the ’polluter-pays’ principle to a ’producer-pays’ principle. In this estimation, we look away from potential taxes on emissions which the end user might pay.

6.2.1 Estimating a Production Fee

The production of one barrel of oil ultimately results in CO_2 emissions added to the atmosphere, when the oil is burnt. A production fee per barrel of oil should reflect the social cost of these CO_2 emissions, working like a Pigouvian tax. The ultimate aim is to produce the socially optimal amount of oil. By applying the framework of Hoel (1994), we can estimate a potential cost-effective production fee.

The willingness to pay for emission cuts is the starting point of deducting a production fee. The highest marginal cost of domestic emission abatement in Norway is between 3,000 NOK and 3,500 NOK per tonne of CO_2, according to a group of researchers from Statistics Norway (Fæhn et al., 2020). They have calculated the cost of measures described in “Klimakur 2030”, which must be done to reach Norway’s emission targets before 2030. This should thus reflect the marginal social cost of emitting one tonne of CO_2. In this scenario, we therefore set the price of emitting one tonne of CO_2 to 3,000 NOK, assuming that there is equal willingness to pay for global as domestic emission cuts.

Hoel (1994) also considers if the country is a net exporter or net importer of fossil fuels. As Norway is a net exporter, the price increase which follows from a supply-side measure is beneficial. In this estimation, we do not find the extent of this effect, but simply note that it pulls in the direction of a supply-side measure.

Lastly, we consider the gross emission reduction and the carbon leakage of the measure, which sum up to net emissions reduction. Statistics Norway has calculated average emission factors from burning petroleum products (Statistics Norway, 2021b). Crude oil can be refined into a great variation of products, which gives slightly different emission factors in scope 3. Based on these numbers, we find the average emission factor for oil products. Therefore, we assume that the emission factor is 0.4310 tonnes of CO_2 per barrel of crude oil. Note that we thereby assume that all oil is burnt, which means that we ignore that some oil is used for plastics and other chemical compounds. The gross emission reduction is thus 0.4310 tonnes of CO_2 per barrel of oil not produced.

We then subtract the carbon leakage to find the net emission reduction. Applying the results found by Fæhn et al. (2017), we find that the net emission reduction is 0.1509 tonnes of CO_2 per barrel. An alternative estimate is done by applying the results by Rystad Energy (2021), leading to a net emission reduction of 0.0086 tonnes of CO_2 per barrel. The great difference is mainly due to different assumptions of price elasticities of supply and demand, which leads to different conclusions on carbon leakage (see section 2.2.2). The net emissions per barrel are multiplied by the cost of emitting one tonne of CO_2, namely 3,000 NOK. The different conclusions on carbon leakage leads to different production fees, summarized by Table 6.7.

Table 6.7: Production fee based on Fæhn et al. (2017) and Rystad Energy (2021).

	Net Emission Reduction	Net Emission Reduction (tonnes CO_2/bbl)	Production Fee (NOK/bbl)
Fæhn et al.	35 %	0.1509	452.55
Rystad Energy	2 %	0.0086	25.86

As seen in Table 6.7, the estimated social cost, and thus production fee, of one barrel of oil varies greatly depending on the assumed carbon leakage. If the authors are right in their respective assumptions, a production fee of either 452.55 NOK or 25.86 NOK would be socially optimal.

6.2.2 Results

We find that a production fee of 25.86 NOK will not give changes to the extraction path. The year of dismantling and total extraction is unchanged from scenario 1, only NPVs changes slightly. In contrast, with the production fee of 452.55 NOK, it will be optimal to change the extraction path on all fields except for Svalin. The optimal solution for most fields is now to stop extraction and dismantle in the first period. Table 6.8 and 6.9 sums up the results when introducing a low and a high fee, respectively.

Table 6.8: Optimal year of dismantling, NPV, total extraction when the production fee is 25.86 NOK/barrel on each field. Changes in parentheses.

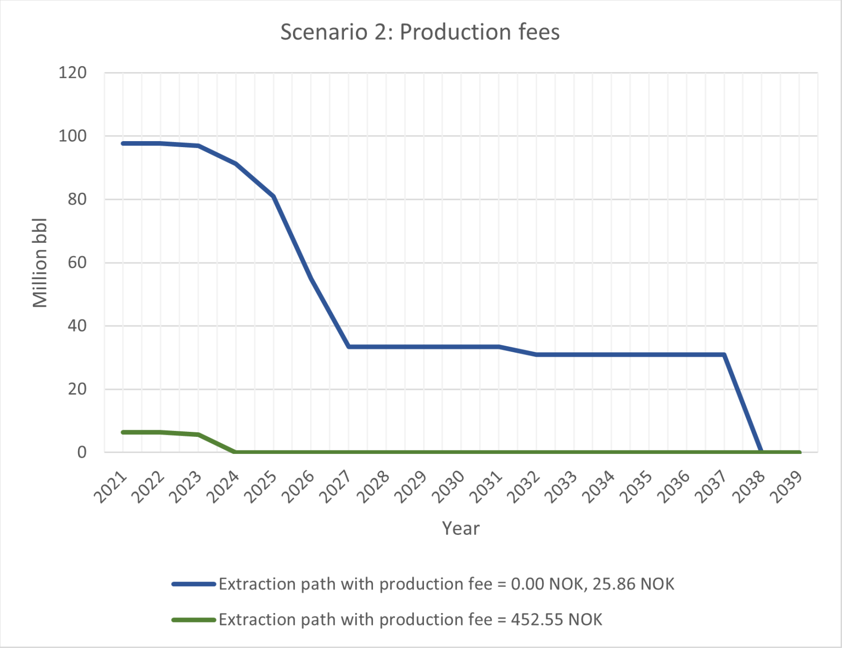
Field	Dismantling	NPV (billion NOK)	Total extraction (million bbl)
Grane	2026	46.23(-2.99)	144.04
Gullfaks	2027	13.93(-1.81)	91.14
Oseberg Øst	2025	0.91(-0.25)	11.95
Skuld	2027	1.84(-0.19)	9.43
Snorre	2038	96.42(-7.30)	526.65
Statfjord Nord	2032	5.06(-0.46)	27.33
Svalin	2024	6.34(-0.41)	18.24
Sygna	2027	0.10(-0.10)	5.03
Tordis	2027	7.51(-0.61)	30.82
Urd	2025	1.24(-0.18)	8.14
Vigdis	2027	17.54(-1.24)	62.23

Table 6.9: Optimal year of dismantling, NPV, total extraction when the production fee is 452.55 NOK/barrel on each field. Changes in parentheses.

Field	Dismantling	NPV (billion NOK)	Total extraction (million bbl)
Grane	2021(-5)	-1.76(-50.98)	0.00(-144.04)
Gullfaks	2021(-6)	-1.76(-17.50)	0.00(-91.14)
Oseberg Øst	2021(-4)	-1.76(-2.92)	0.00(-11.95)
Skuld	2021(-6)	-1.76(-3.79))	0.00(-9.43)
Snorre	2021(-17)	-1.76(-105.48)	0.00(-526.65)
Statfjord Nord	2021(-11)	-1.76(-7.28)	0.00(-27.33)
Svalin	2024	-0.36(-7.11)	18.24
Sygna	2021(-6)	-1.76(-1.96)	0.00(-5.03)
Tordis	2021(-6)	-1.76(-9.88)	0.00(-30.82)
Urd	2021(-4)	-1.76(-3.30)	0.00(-8.14)
Vigdis	2021(-6)	-1.76(-20.54)	0.00(-62.23)

Figure 6.5 illustrates the aggregated extraction path.

Figure 6.5: Aggregated extraction paths with current policies, two different production fee scenarios.



6.2.3 Sensitivity Analysis

Production Fee

In the attempt to estimate a cost-effective production fee, we come up with two quite different levels of fees, which resulted in totally different outcomes with respect to extraction paths. It is interesting to see how extraction paths could be different in the case of a production fee somewhere in between these estimates. Therefore, we test for a production fee of 100.00, 200.00, 300.00, and 400.00 NOK to see how extraction paths change. Figure 6.6 illustrates the respective extraction paths.

Figure 6.6: Aggregated extraction paths with current policies, in different production fee scenarios.

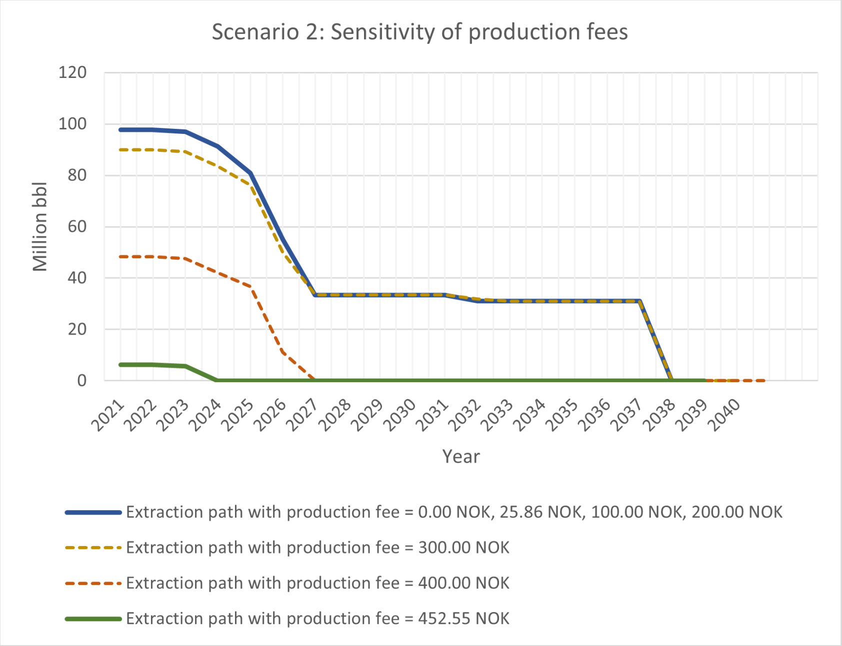


Table 6.10 lists the fields changing their extraction path in the case of a production fee of 300.00 NOK.

Table 6.10: Fields where optimal year of dismantling, and total extraction changes with a production fee of 300.00 NOK. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Gullfaks	2021(-6)	0.00(-91.14)
Oseberg Øst	2021(-4)	0.00(-11.95)

Table 6.11 lists the fields changing their extraction path with a production fee of 400.00 NOK.

Table 6.11: Fields where optimal year of dismantling, and total extraction changes with a production fee of 400.00 NOK. Changes in parentheses.

Field	Dismantling	Total extraction (million bbl)
Gullfaks	2021(-6)	0.00(-91.14)
Oseberg Øst	2021(-4)	0.00(-11.95)
Snorre	2021(-17)	0.00(-526.65)
Statfjord Nord	2021(-11)	0.00(-27.33)
Sygna	2021(-6)	0.00(-5.03)
Tordis	2021(-6)	0.00(-30.82)
Urd	2021(-4)	0.00(-8.14)

7 Discussion

Our research and the following results have culminated into four main findings, which we present and discuss individually. Further, we discuss the external validity of our research. Lastly, we point out the limitations of our study, in close connection with suggestions on further research.

7.1 Discussion of Results

FINDING 1 *- The currently announced climate policy does not affect the extraction path of oil on the NCS, given the expected oil price of 552.5 NOK.*

Our results suggest that the currently announced climate policy, formed by a carbon tax on emissions and EU ETS emission quotas, is nowhere near affecting the oil supply from existing fields on the NCS through increasing production costs. Even an extreme increase of the carbon price to reach 10,000 NOK per tonne of CO_2 before 2030 did not cause a change to the extraction path. This is coherent with Massetti and Sferra (2010), Bauer et al. (2013) and Smulders and Werf (2008), who find that conventional oil will be extracted under aggressive climate policies. We have not considered how an increase in the local carbon price will affect local demand and subsequently the world price of oil.

The conclusion changes only slightly when we apply a lower expected oil price of 255 NOK. Given a lower oil price expectancy, extraction turns unprofitable for two out of the eleven fields. The moderate change in results is in line with Equinor's statements of being profitable even with low oil price expectancies, and provides evidence for the great robustness of the extraction paths.

Even under increasingly aggressive climate policies on the demand side, oil extraction turns out to be extremely profitable. Even if policies cause a fall in the long-term oil price, oil extraction is associated with great profits. It is unlikely that we will ever see similar profits in the renewable energy sector, as there is no scarcity of wind nor sunlight, yielding no resource rents. The implication is that even though realizing that renewable energy is the long-run solution, one cannot avoid the fact that under the current development, oil will be profitable for many years to come.

The fields in our sample have a higher carbon intensity than the average of fields on the NCS. They also likely have relatively higher production costs because they are in the tail phase of production. This means that the carbon price is lower, and the profit per barrel higher, on the average field on the NCS. We can therefore conclude that today's climate policy will have a negligible or no impact on the extraction path of all existing fields on the NCS in the next decade.

When it comes to fields that are yet to be developed, newer fields have a lower carbon intensity than the fields in our sample, resulting in an even lower carbon price per barrel of oil extracted. However, it is possible that the carbon price will make a difference when deciding to build new projects. In those projects, the decision-relevant costs will be higher, since initial investments also need to be taken into account before deciding to develop a field. The carbon price might then make new projects marginally unprofitable.

The petroleum sector is the only sector that is subject to both the EU ETS and the carbon tax. Given our finding that policies have no impact on extraction paths on existing fields, this emerges as fair treatment.

FINDING 2 - *The extraction path is by far more sensitive to changes in the oil price and exchange rates than to changes in the carbon price.*

The results reveal that the oil price and the USD/NOK exchange rate is a much bigger concern to oil companies than the carbon price. Whereas the carbon price is expected to follow a steady increase over time, the oil price and the exchange rate are volatile variables. And even big changes in carbon price will not impact the NPVs as dramatic compared to big changes in the oil price, due to the low carbon intensity on the NCS. Still, even with a low oil price expectancy of 255 NOK, the extraction path remains the same for most of the fields.

A single oil company can unlikely impact the oil price nor the exchange rate, but it can take actions to reduce the carbon price per barrel. This suggests that although the carbon price does not affect the extraction path, it is likely that it would affect decisions to reduce emissions in production, which takes us to the next finding.

FINDING 3 *- Today's climate policies give incentives to reduce emissions in production, rather than reducing production volume.*

The alternative cost of business as usual, is to invest in low-carbon technology and hence reduce emissions in production. We argue that the carbon price is large enough to incentivize oil producers to reduce emissions. It provides a rationale and an incentive to hunt carbon efficient solutions, in particular for fields in late life as cost balance becomes even more important, with smaller margins.

This incentive to lower emissions in production leads to investments in emission-reducing technologies. A perhaps ignored issue of today's climate policy is therefore the issue of carbon lock-in, as described by Unruh (2002). Institutional, social and technological investments make it difficult to make a shift toward other industries. Great investments are done to reduce emissions in oil extraction, perhaps on the expense of other technologies. An example of this is the floating wind power park Hywind Tampen, which will provide power for the production at Gullfaks and Snorre. The park, at a cost of close to five billion NOK will prevent 200,000 tonnes of CO_2 emissions each year. The size and commitment of these investments build on the threshold of leaving the oil industry behind.

Keeping the example of Hywind Tampen in mind, we may revisit the report by Rystad Energy (2021). The report claims that supply-side policies will impact technology development negatively. They argue that a cut in petroleum production entails a set-back in the development of low-carbon and green technologies where one can make use of petroleum knowledge and infrastructure. Examples of such technologies are carbon capture and storage, hydrogen and wind power. While Hywind Tampen is made to support petroleum production, the technology and knowledge developed in this project is not limited to the petroleum industry. Rystad Energy also points out that the cash flow from petroleum allows investments in new technologies with less financial risk, leading to faster maturing of new technologies. In conclusion, it is hard to tell the actual presence of carbon lock-in on the NCS.

FINDING 4 *- A cost-effective production fee might change the extraction path at several fields, depending on level of fee.*

In terms of a fossil fuel producing country, the carbon price creates incentives to reduce emissions in production, while a production fee will directly impact the production of oil. Similar to Rosendahl (1994), we find a significant decrease in the resource wealth (NPV) when introducing a production fee.

But there is great uncertainty in the optimal level of fee, due to the opposing research on the amount of carbon leakage related to cuts in oil production on the NCS. This makes calculating the correct production fee a difficult task. Using different research, we found two levels of leakage, resulting in fees of either 25.86 NOK or 452.55 NOK. The first made no change in the extraction path of our sample, while the latter resulted in every field shutting down except one.

Further, the production fee is based on the net global emissions stemming from the combustion of Norwegian oil. As the lion's share of Norwegian oil is exported, the fee would not be effective in contributing to the target set by the Paris Agreement, as it only consider domestic emissions.

In this study, we have looked at policies for Norway in isolation. The problem of carbon leakage can be reduced by agreeing with other producers on a supply-side measure. A global production fee, as suggested by Rosendahl (1994), would be more efficient than the national fee investigated in this thesis. According to Asheim et al. (2019), if a coalition agrees upon a treaty to limit fossil fuel supply as a complement to the Paris Agreement, it will raise prices also outside the coalition and thus help keep the global consumer price high, even among free-riders.

Lazarus and van Asselt (2018) have pointed out that a supply-side policy is politically difficult to put in action. Petroleum companies might consider the sudden implementation of production fees at this point unreasonable, especially considering sunk investment costs on existing fields. A more feasible approach might be to only make the production fee eligible for undeveloped fields, such that this cost is considered in initial investment decisions.

7.2 External Validity

External validity refers to the extent of how much the results of a study can be expected to apply in other settings. In our case, we may ask the questions: As in Norway, are announced climate policies no threat to extraction paths on fields across the globe? Will the production fee be of similar size and make a similar impact as found in our results?

For the first question, due to the high margins in oil production, it is likely that the results of this paper holds for most existing fields globally. However, the estimated effects from the NCS are not directly transferable to other countries. The extraction path on fields on the NCS is not very exposed to changes in carbon prices, as the carbon intensity is relatively low. Masnadi et al. (2018) show that the estimated carbon intensity varies greatly across countries. Logically, more emitting oil producers will be more exposed to changes in carbon prices. On the other hand, the results are based on national specific climate policies. Norwegian climate policy is among the strictest in the world, which means that operators in other countries pay less for emissions. The results thus depend on climate policies, cost structure and carbon price in the respective countries and on specific fields. The answers to these doubts may easily be obtained by using our model on fields of interest.

The second question addresses the size and impact of the production fee. The estimation of the production fee was based on the marginal willingness to pay for emission reduction, which was assumed to be the social cost of carbon. The social cost of climate change is bigger in more climate-exposed countries. Despite this, it is likely that the willingness to pay for abatement is higher in Norway than most countries. The estimation was also based on carbon leakage, which will differ across countries, due to different carbon intensities in production and differences in market power. The implementation of a fee would affect the NPVs, but the extent of the impact, and whether it affects the extraction paths, depends on the size of the fee and profitability on the field. While results on production fees are not directly transferable to fields in other countries, a similar approach may be used to estimate fees in different settings.

7.3 Limitations of the Study and Further Research

The scope of our research is limited, which means there are some shortcomings to be addressed. We take a look towards the limitations of our study, and discuss further research in the following.

First, our model has some shortcomings. We use a deterministic model, assuming constant costs, carbon intensities, prices, and extraction capacities. An development of the model could consider increasing marginal costs. As the future is unpredictable, so are the parameters. Our model does not account for this unpredictability. A model which better accounts for the oil price fluctuations, for example with the oil price as a stochastic variable, might therefore be better suited. Further, our model is specified in years. It is reasonable that investment decisions happen on a yearly basis. The choice of yearly time periods means that marginal changes in extraction paths within a year is not observed. A model with monthly or quarterly time periods would be able to predict extraction paths more specifically. Another issue of choosing yearly time periods emerges when there only remains a small portion of oil in the reservoir. The fixed yearly cost might then cause the model to not extract the last portion. In reality, we may think that all recoverable oil would be extracted at the beginning of the year.

Further, our model investigates the fields in isolation. It does not take into account that the fields are interconnected and that the shut-down of one field has implications for other fields. An unprofitable field might still produce as adjacent fields send their oil and gas to the respective field. And, very often new reservoirs can be drilled from existing installations, creating opportunities where there are none for a stand-alone development. Further research may investigate how these connections affect production decisions, as well as investment decisions.

It can be debated whether operational costs really can be seen as variable, as many of the operational costs have a fixed nature in the short term. For example, installations cannot operate below a certain level of employees. An Equinor employee estimated that 70-80 percent of operational costs are not scalable (Equinor employee, personal communication, November 15, 2021). The distinction between fixed costs and unit costs is not decisive in our case, as we observe that the optimal production level is always to produce at a maximum level.

While not affecting production decisions, the carbon price still forms a significant cost for the petroleum companies. Petroleum companies likely implement and develop new technologies to adjust for an increase in the carbon price. This observation is confirmed by the fact that the Norwegian petroleum sector has decreased intensity over the last years. Further research may look into investment decisions and emission reductions in the oil sector when adjustments are done to climate policies. What will be the key focus for oil producing companies in the coming years with pressure from the outside - build new assets with low-carbon intensity technology or reduce carbon intensity on already existing fields? Or maybe a combination of both?

In this thesis, we consider a production fee as a supply-side policy measure, though there are many types of supply-sides to choose from. It would be interesting to look into how different supply-side policies would affect extraction path as well as global emissions. One supply-side policy is to set a cap on production, as opposed to the cap on emission, following a producer-pay principle. Another supply-side policy approach is to restrict the number and size of areas open for exploration and licensing on the NCS. Exploration and licensing are already controlled by the Norwegian government today.

When calculating costs related to oil production, we only consider costs directly related to the fields. This means that we do not consider costs of transport or potential other costs which might be relevant. Further, we have not analyzed emissions in transport (scope 2). We do not look into other types of emissions, such as methane and other GHG emissions, or other negative externalities, such as damage to nature. Positive externalities from oil production are left out.

As we use an exogenous oil price in our model, we have not specifically considered the effect of the climate policy on the oil price. If climate policies reduce the world demand, and therefore the oil price, the supply of oil might be affected through this channel.

We assume equal willingness to pay for emission cuts on the supply side and the demand side. A challenge to this is that in reality, a country could potentially have higher utility related to cutting emissions on the demand side. Reducing the supply of oil might result in environmental benefits shared by all nations, while cutting emissions on the demand side could have local benefits like less air-pollution or fulfillment of international agreements. The real value of cutting production in the oil sector might therefore be lower than policies on the demand side. We also look away from potential taxing for the end user, which triggers the risk of double counting. With this mark, we hope that further research is done on how to price the production of oil.

8 Conclusion

The purpose of this thesis is to contribute to existing research by looking at the effect of climate policies on the supply of oil on the NCS. In order to simulate the effect of climate policies, we have estimated costs and carbon intensities for the fields of interest. We use these estimations together with field-specific information of extraction capacity and oil reserves in a self-developed optimization model to study the optimal oil extraction path for different fields of interest. The purpose is to use this simple model that maximizes NPV to investigate how a producing field's extraction path changes, subject to different climate policy scenarios.

The thesis addresses the differences between demand-side and supply-side policies. Climate policies on the demand side are more common, with the carbon tax and the EU ETS emission quotas as examples. We study how the current demand-side climate policy, and a potential supply-side production fee, affect the extraction path of oil through increasing production costs.

The results imply that today's climate policy for the period 2021-2030 does not affect the extraction path of existing oil fields on the NCS. As newer fields are built to have lower carbon intensity, they will have a lower total carbon price. Therefore, the carbon price is assumed to have even less impact on the extraction path at newer fields than on mature fields.

We observe that the profitability of fields is far more sensitive to changes in the oil price and the exchange rate. However, these variables are volatile, and would likely not affect the supply of oil unless the price stays low. A prolonged expectancy of low oil price will affect the extraction paths on the oil fields.

While we see that today's climate policy does not result in a change of the extraction path, we argue that the fields will have incentives to emit less in doing so. The more recoverable oil, and the higher the carbon intensity, the higher the total carbon price. This leads to higher incentives to invest in low-carbon solutions to reduce the carbon intensity and lower the carbon price.

We have attempted to estimate a cost-effective production fee and looked at how the extraction path is affected by such a fee. We find that a cost-effective measure could be either 25.86 NOK or 452.55 NOK per barrel of oil, depending on different research. The former would not affect the extraction path, whilst the latter will significantly change the extraction path. Even though a correct fee is difficult to calculate, policy implications of a production fee is that this will impact the oil supply directly and at the same time address global emissions.

One last implication of the results is that to directly downsize oil production, climate policies need to be implemented on the supply-side of oil production. Today's climate policy's primary function on oil production is to reduce emissions in the extraction process. If we are to reach the goals of the Paris Agreement, lower emissions when extracting fossil fuels is not enough. Large parts of the world's oil reserves simply have to remain in the ground.

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