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Norway's Ambitious Climate Targets - A Threat to the Development of Floating Offshore Wind?

A Study of the Economic Attractiveness of Off-Grid Floating Offshore Wind as a Means to Decarbonize the Norwegian Continental Shelf

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Norway's Ambitious Climate Targets - A Threat to the Development of Floating Offshore Wind?

A Study of the Economic Attractiveness of Off-Grid Floating Offshore Wind as a Means to Decarbonize Oil and Gas Platforms on the Norwegian Continental Shelf

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Abstract

Rising concerns about climate change compel nations to adopt ambitious and transformative climate targets. Accordingly, the Norwegian government has advocated for the vast oceanic wind resources available on the Norwegian continental shelf (NCS) to play an important role in decarbonizing its oil and gas industry. To realize this endeavor, floating offshore wind technology is required as the NCS primarily consists of deep waters. With comprehensive experience and knowledge of offshore operations from the petroleum sector, Norway is uniquely positioned to kick-start the national offshore wind industry through decarbonizing oil and gas platforms on the NCS. As floating wind is an immature technology, small-scale projects are vital to driving technological innovation and cost reduction without incurring the risk of extensive losses. This paper studies the economic attractiveness of small-scale off-grid floating offshore wind farms (OWF) as an electrification alternative to corporate operators of oil and gas platforms on the NCS. Multi-objective decision analysis is applied to depict the decision problem realistically. Furthermore, we take a real options approach in order to account for uncertainties and managerial flexibilities inherent in the problem. We find that given the government's carbon tax strategy for the following decades, off-grid floating OWFs are not competitive to power from shore solutions. Additionally, as an off-grid OWF may only partially electrify platforms, high expected carbon taxes lead this solution to be an inferior alternative even with generous subsidies and technological improvement. For off-grid OWFs to represent a competitive electrification alternative for platforms on the NCS, carbon taxes must remain around their current level. Therefore, our results suggest that the successful implementation of small-scale off-grid floating OWFs on the NCS must be driven by policy and actively supported by the government to trigger corporate investment and reach the goal of developing a national offshore wind industry.

Sammendrag

Økende bekymring for konsekvensene av klimaendringer har ført til ambisiøse og omfattende klimamål verden rundt. I den forbindelse har Norges regjering gått i bresjen for at de betydelige havvindressursene på norsk kontinentalsokkel skal ta en viktig rolle i å dekarbonisere norsk olje- og gassindustri. På grunn av kontinentalsokkelens dybde må flytende havvindteknologi tas i bruk for at dette skal bli en realitet. Norge innehar stor kunnskap knyttet til offshore olje- og gassvirksomhet, og er derfor i en unik posisjon til å utvikle den norske havvindindustrien gjennom dekarbonisering av sokkelen. Flytende havvind er foreløpig en umoden teknologi der utviklingen av småskala prosjekter er avgjørende for å drive innovasjon, samt redusere kostnader, uten for store økonomiske tap. Formålet med denne artikkelen er å undersøke hvorvidt småskala off-grid flytende havvindparker er attraktivt som et elektrifiseringsalternativ for olje- og gassoperatører på norsk sokkel. Vi bruker flermåls beslutningsanalyse for å realistisk beskrive valget operatøren står ovenfor. Videre bruker vi realopsjoner for å ta usikkerhet og beslutningstakerens fleksibilitet i betraktning. Resultatene våre tilsier at småskala off-grid flytende havvind ikke er konkurransedyktig med kraft fra land gitt regjeringens planlagte skattepolitikk for de neste tiårene. Vår studie viser at selv med omfattende subsidier og teknologiske fremskritt forblir småskala off-grid flytende havvind et mindre ettertraktet alternativ grunnet høy CO_2-avgift. Kun dersom avgiften forblir rundt sitt nåværende nivå i flere tiår vil havvind være et konkurransedyktig alternativ for elektrifisering av norsk sokkel. Dette indikerer at politiske virkemidler må tas i bruk for å insentivere privat investering i havvindprosjekter, noe som er kritisk for å kunne oppnå regjeringens mål om et norsk havvindeventyr.

Preface

This thesis is submitted as the concluding part of our Master of Science degrees in Industrial Economics and Technology Management, with specialization in Financial Engineering, at the Norwegian University of Science and Technology (NTNU). The thesis is written as a scientific paper. After careful consideration of different potential publication outlets we have decided to aim for publication in one of the following journals: *Energy Economics* or *Energy Strategy Review*.

We would like to sincerely thank our supervisor Professor Verena Hagspiel and co-supervisor Professor Reidar Brumer Bratvold for their helpful guidance, inspiring discussions, and constructive feedback throughout this challenging endeavor. Their comprehensive knowledge and willingness to share ideas, thoughts, and relevant theory was greatly appreciated. They allowed us to explore and better grasp the fields of real options and decision analysis.

Trondheim, June 11, 2021

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Acronyms

CA Competitive advantage

CAPEX Capital expenditure

CC Combined carbon

DP Dynamic programming

EUA European Union allowance

GBM Geometric Brownian motion

GHG Greenhouse gas

LCOE Levelized cost of energy

LSM Least squares Monte Carlo

NCS Norwegian continental shelf

NPV Net present value

O&G Oil and gas

OWF Offshore wind farm

PFS Power from shore

PV Present value

RO Real option

WTI West Texas Intermediate

Chapter 1

Introduction

Climate change is one of the most pressing issues of our time. To address this issue, Norway has set an ambitious goal of reducing carbon emissions by at least 50% by 2030, compared to 1990 levels (Norwegian Ministry of Climate and Environment, 2016). The Norwegian oil and gas (O&G) industry is responsible for 28% of the national greenhouse gas (GHG) emissions. These emissions predominantly arise from the use of on-site gas turbines to power offshore platform operations (Norwegian Environment Agency, 2020a; Norwegian Petroleum Directorate et al., 2020). This has made the industry a major target for emission reductions. As 98% of electricity produced in Norway stems from hydropower, electrification by connecting O&G platforms to the national grid using power from shore (PFS) has been the primary alternative to mitigate emissions since 1996 (Statistics Norway, 2019; Norwegian Petroleum Directorate et al., 2020). With the emergence of offshore wind as a viable power source, platform operators and policy-makers have expressed interest in using offshore wind farms (OWF) as an alternative to PFS (Eik, 2020; Norwegian Petroleum Directorate et al., 2020; Vassbotn, 2020). As Norwegian O&G platforms are located offshore in waters with depths primarily exceeding 100 m, the applicability of commercial fixed-bottom technologies is limited due to depth constraints. Floating offshore wind is not limited by water depths, and is therefore more suitable for most platforms on the Norwegian continental shelf (NCS) (International Energy Agency, 2019a; The Norwegian Water Resources and Energy Directorate, 2020). However, the technology is currently immature, and only pilot projects have been developed. Companies operating platforms on the NCS possess significant knowledge and expertise with offshore technologies. For this reason, both the industry and the Norwegian government consider decarbonizing O&G platforms with floating OWFs as a potential learning step to reduce costs, gain experience, and kick-start the Norwegian offshore wind industry (Eik, 2020; Norwegian Ministry of Petroleum and Energy, 2020c; Vassbotn, 2020). In this attempt, for the first time in Norwegian history, the authorities made two locations[1] on the NCS available for large-scale offshore wind developments on the 1st of January 2021 (Norwegian Minister of Petroleum and Energy Tina Bru, 2020). This announcement has sparked massive interest from both national and international energy companies (Torbjørnsdal, 2020; Aker Offshore Wind, 2021; Arendals Fossekompani, 2021; Eni, 2021; Equinor, 2021b; Haugaland Vekst, 2021; Norseman Wind AS, 2021; Renewables Now, 2021; Statkraft, 2021). However, the government does not expect projects in these areas to be completed prior to 2030 (Skårderud, 2021). In the meantime, it is therefore of national interest to reduce costs and drive innovation through smaller projects.

This paper aims to investigate the economic feasibility of small-scale[2] off-grid floating OWFs as an electrification alternative for O&G platforms on the NCS. We aim to contribute to the ongoing discussion by studying the possibility of decarbonizing the Norwegian O&G industry as a means to cut emissions while increasing expertise and reducing costs. We take the perspective of a corporate decision-maker to assess the impacts of policies, technological improvements, and market factors on the corporate interest in floating offshore wind on the NCS. Furthermore, we apply multi-objective decision analysis to realistically depict the decision problem faced by operators on the NCS. The decision-maker in question considers three objectives in his analysis: maximizing net present value (NPV), minimizing GHG emissions, and maximizing competitive advantage (CA) in the floating offshore wind industry. We treat investments into the two renewable power supply alterna-

[1]These are Utsira Nord and Sørlige Nordsjø II, with a designated total capacity of 4,500 MW. Utsira Nord is suitable for floating OWFs, while Sørlige Nordsjø II is located in relatively shallow waters where both technologies are applicable.

[2]We consider OWFs with a rated power below 100 MW as small-scale.

tives, PFS and an off-grid floating OWF, as mutually exclusive. Taking a real options (RO) approach allows us to account for managerial flexibility in terms of delaying investment. Our solution approach is based on least squares Monte Carlo (LSM). Performing extensive sensitivity analysis, we provide insight into technology choice and investment timing for different market conditions and future scenarios.

As floating offshore wind is a new technology and still in the development phase, most existing studies focus on technical feasibility, design, and impact of weather conditions on operations (Yan et al., 2016; Calderer et al., 2018; Tong et al., 2018; Qu et al., 2018; Wen et al., 2019; Jacobsen and Godvik, 2021; Liu et al., 2021). With the technical success of recent pilot projects such as Hywind Scotland and Windfloat Atlantic, research on economic feasibility has ensued. del Jesus et al. (2017) present a methodology for optimal site selection based on the impact of wind resource availability on financial indicators such as NPV and internal rate of return. Their methodology is devised to be site-independent and applicable at any spatial and time horizon. Baita-Saavedra et al. (2020) develop a method to analyze the economic feasibility of a novel floating offshore wind structure. They apply the method to a representative case in Portugal with uncertain electricity tariffs and capital costs. Castro-Santos et al. (2020) present a method to determine the economic feasibility of floating OWFs in Portugal. In their study, two scenarios with different electricity tariffs are evaluated for several floating substructures. The studies mentioned above all focus on floating OWFs that are connected to national grids. To the best of our knowledge, there are no contributions that consider floating OWFs as an off-grid electrification alternative for offshore O&G platforms.

In order to account for uncertainty and managerial flexibility in analyzing offshore wind projects, several studies take a ROs approach. Iniesta and Barroso (2015) develop a methodology for evaluating investments in offshore wind in Denmark, based on ROs possessed by the authorities. Schwanitz and Wierling (2016) employ a ROs model with empirically-derived parameter values to evaluate offshore wind power investments. Their results indicate that policies should target offshore wind load factor and material efficiency instead of project size. Kitzing et al. (2017) present a ROs model for wind projects, considering investment timing and capacity sizing. Their model includes capacity constraints and a single stochastic process that capture multiple correlated uncertainties, allowing for closed-form solutions. The model is applied to a case study of offshore wind projects in the Baltic Sea to quantify the value of different investment incentives. Kim et al. (2018) propose a decision-making model based on ROs valuation to analyze the economic feasibility of fixed-bottom OWFs under climate uncertainty. Considering expansion options, they find that managerial flexibility provided by the ROs effectively reduces risk and increases long-term profitability in a South Korean case study. Li et al. (2020) employ a LSM approach combined with binomial tree scenario generation to numerically identify optimal feed-in tariffs for Chinese offshore wind power investments. The studies mentioned above only consider fixed-bottom technologies in a very different developmental stage compared to pre-commercial floating technology. Furthermore, existing methodologies do not focus on offshore wind in the context of a mutually exclusive investment decision. Accordingly, they are less suitable for the decision problem of choosing between a floating OWF and other electrification alternatives. Therefore, we see a clear literature gap considering uncertainty and managerial flexibility for mutually exclusive floating offshore wind investment opportunities.

Standard ROs literature is generally limited to account for the single objective of maximizing profit. Literature considering additional perspectives is scarce. Among the few exceptions are Boomsma et al. (2012) and Nagy et al. (2021), who account for a welfare perspective when studying the impacts of policy measures on the attractiveness of renewable energy investments. In addition, Huisman and Kort (2015) present a duopolistic framework that compares a firm's optimal investment decision to the optimal welfare decision. These papers evaluate and compare profit-maximizing and welfare-maximizing decisions. However, in the real world, decision-makers often face complex decision problems where several objectives have to be taken into consideration (Bratvold and Begg, 2010). This has particularly been the case for O&G companies as increased emphasis on emission reductions and strategical repositioning has transformed the decision landscape. Therefore, an extension of the ROs literature incorporating multi-objective decision analysis when evaluating investment opportunities is needed to depict real-world problems realistically.

The key contributions of this paper are twofold. Firstly, we propose a method to apply ROs valuation to multi-objective decision problems by employing LSM. The methodology expands on existing ROs literature that mainly applies LSM to problems where profit-maximization is the sole objective. This significantly enlarges the application area of ROs valuation, as decision-makers in complex real-world problems often have multiple objectives. Secondly, we investigate the economic attractiveness of small-scale off-grid floating OWFs to decarbonize O&G platforms on the NCS. Our findings suggest that CO_2-taxes become too high for off-grid OWFs to be a competitive electrification alternative under stated policies. Policy changes coupled with increased governmental subsidies or cost reductions beyond expected levels are required for smaller off-grid floating OWFs to become a viable solution for private O&G companies in the short term.

The remainder of this paper is organized as follows: In Chapter 2, we formulate the decision problem and describe the modeling approach, followed by a presentation of the developed solution approach based on LSM. In Chapter 3, we introduce the reader to conditions surrounding O&G operators on the NCS and parametrize the case study. In Chapter 4, we present our results, perform a sensitivity analysis and discuss insights. Finally, Chapter 5 concludes our essential findings and suggestions for areas of future research.

Chapter 2

Methodology

In this chapter, we present the problem considered in this paper and our modelling approach. In Section 2.1 the multi-objective decision problem is formulated. In Section 2.2, we develop a model to solve the decision problem. Additionally, we elaborate on the objective value modeling, stochastic state variables, and the LSM solution approach.

2.1 Problem formulation

In this paper, we consider a representative case of an operator's O&G platform on the NCS. The platform is considered relatively new. Operators of older platforms with short remaining lifetimes have less managerial flexibility regarding electrification and are less relevant for the scope of this paper. Currently, the platform is powered by burning natural gas. As a result of increasing taxes on GHG emissions and lost revenue due to burning gas instead of selling it, the operator considers electrification alternatives to potentially increase profits without impacting the O&G-related operations. In addition to increasing profits, the operator may have secondary preferences. By establishing a value hierarchy, these preferences can adequately be taken into account. A value hierarchy is a tool from decision analysis that decomposes values to identify relevant objectives in the decision situation (Bratvold and Begg, 2010). This allows the operator to get a clearer picture of the decision situation and make well-informed decisions.

Based on the situation presented above, the values and corresponding objectives identified for the operator are illustrated in Figure 2.1. The value hierarchy is based on the assumption that the principal value of the operator is to increase shareholder value. The operator considers this achievable by ensuring long-term profits and improving public image. To improve public image, the operator believes that participating in reaching global and national goals as well as increasing attractiveness to investors are the main drivers. He regards minimizing GHG emissions, maximizing national security of electricity supply and job creation in Norway as the relevant objectives connected to these values. Finally, to ensure long-term profits, he considers increasing profits from current and future operations, and securing subsidies to be most important. The objectives related to these values are maximizing the NPV of the platform, CA in the floating offshore wind industry, national security of electricity supply, industry goodwill, and minimizing GHG emissions.

The operator deems the following three objectives to be the most relevant: maximizing NPV, minimizing GHG emissions, and maximizing CA in the floating offshore wind industry. The other objectives are either less relevant, difficult to quantify, or connected to values better represented by one of the chosen objectives. Accordingly, he disregards them to reduce complexity. The current public perception in Norway is rather critical towards O&G operations. Therefore, he believes that decreasing GHG emissions is essential to improve company reputation. O&G operations on the NCS are expected to decrease with time due to the scarcity of reserves and climate policies (International Energy Agency, 2019b). Hence, to ensure future profits, the operator desires to partake in the development of floating OWFs in order to position himself in the emerging floating offshore wind industry and obtain CA. Consequently, the operator faces a multi-objective decision problem with three objectives.

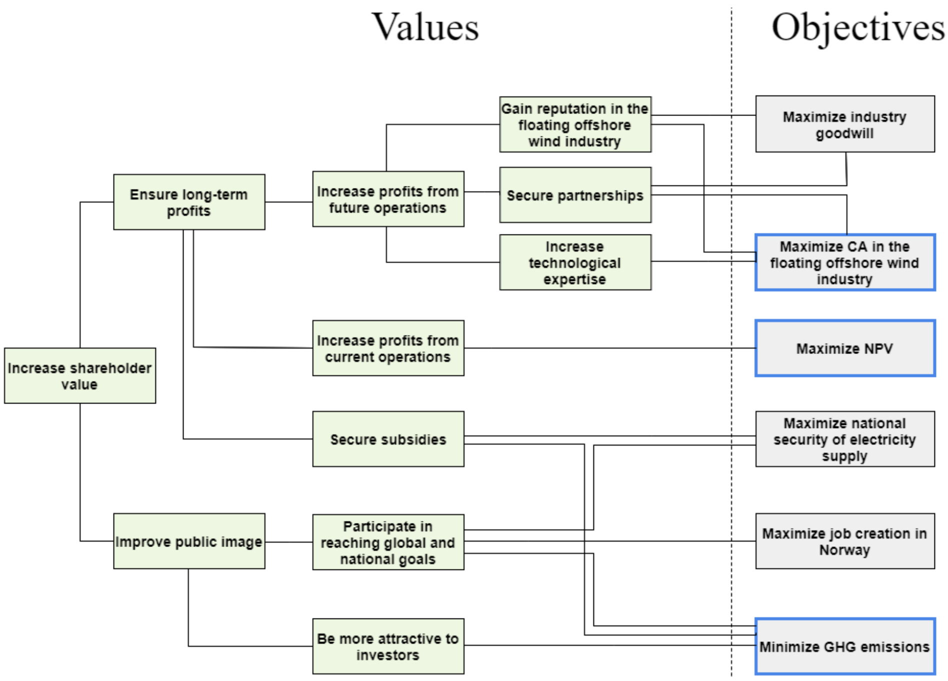


Figure 2.1: A value hierarchy showing the operator's values and corresponding objectives. The objectives encompassed by a blue line are considered most important by the operator.

Currently, the available electrification alternatives for platforms on the NCS are PFS and off-grid OWFs. A PFS solution enables full electrification of the platform, while an off-grid OWF may only provide partial electrification due to intermittency issues (Norwegian Petroleum Directorate et al., 2020; Equinor, 2021c). In 1996, the first PFS solution was implemented on the NCS, and the technology has represented the only electrification alternative so far. Certain PFS projects have been limited by grid constraints, and therefore only provided partial electrification of platforms (Norwegian Petroleum Directorate et al., 2020). The operator does not believe that this will be a constraint, as the energy demand of a single platform is unlikely to jeopardize the national security of electricity supply. Furthermore, Statnett, the Norwegian transmission system operator, considers the current available capacity in the Norwegian grid to be adequate (Statnett, 2019). The first floating OWF, Hywind Tampen[3], is expected to be in operation by 2022. Grid-connected OWFs have yet to be built on the NCS, and no such projects are expected completed before 2030. Therefore, the operator only considers an off-grid solution. Consequently, due to the lack of other mature alternatives, the operator only considers full electrification with PFS and partial electrification with an off-grid floating OWF as viable options to electrify the platform. The OWF is the only alternative that can obtain CA, while PFS, and to a lesser extent the OWF, reduce GHG emissions. Hence, all objectives are accounted for by at least one of the alternatives. Table 2.1 summarizes the objectives and alternatives considered in this study.

Table 2.1: The objectives and alternatives relevant to the operator's decision problem.

Objectives	Alternatives
NPV: Maximize platform NPV	**Never**: Continue to burn natural gas
GHG: Minimize GHG emissions	**OWF**: Partial electrification with an off-grid floating OWF
CA: Maximize CA in the floating offshore wind industry	**PFS**: Full electrification with PFS

[3]Hywind Tampen will be an 88 MW off-grid floating OWF whose purpose is to partially electrify five platforms on the NCS (Equinor, 2021c).

2.2 Model

The operator of the O&G platform faces a mutually exclusive investment problem. He can invest in either full electrification through PFS or partial electrification through an off-grid floating OWF. Alternatively, he continues with the status quo, powering the platform by burning natural gas. The operator has managerial flexibility with respect to choosing the investment timing. We assume that he revisits the investment decision once a year, given that he has not already invested. Both the OWF and PFS alternatives require significant capital investments in infrastructure. The future profitability of the projects is uncertain as it depends on several parameters whose future values are unknown. To be able to correctly account for uncertainty and managerial flexibility, we take a ROs approach. The financial equivalent of the option to invest in PFS and the OWF, respectively, is a Bermuda-styled call option[4].

As argued in the previous section, the operator considers three objectives when deciding on future platform power supply: maximizing NPV, minimizing GHG emissions, and maximizing CA. As multiple objectives with different units are relevant to the operator, we adopt a method that allows for a reasonable comparison between them. We choose to convert the non-monetary objectives related to GHG emissions and CA to a monetary scale using scaling constants. The scaling constants represent the value in NOK of one unit of GHG emission and CA, respectively. Hence, the objective value obtained is given by

$$\psi(\vec{x}_t, \vec{y}_t) = w_1 \cdot \text{NPV} - w_2 \cdot s_2 \cdot \text{GHG} + w_3 \cdot s_3 \cdot \text{CA}, \tag{2.1}$$

where $\vec{x}_t$ and $\vec{y}_t$ are binary decision variables taking the value one if investment in the OWF or PFS, respectively, is undertaken in year t and zero otherwise. w_i, for i $\in \{1,2,3\}$, denotes the weight assigned to each objective. s_i for i $\in \{2,3\}$ denotes the scaling constant of the non-monetary objectives. The weights are used to model the operator's relative preference of the objectives, with $w_1 + w_2 + w_3 = 1$.

The operator's objective is to select the values of $\vec{x}_t$ and $\vec{y}_t$ that maximizes the obtained objective value. As he assesses whether to invest in the mutually exclusive opportunities once a year, the problem is formulated as the discrete optimization problem described by

$$\max_{x,y} \quad \psi(\vec{x}_t, \vec{y}_t) \tag{2.2a}$$

$$\text{subject to} \quad \sum_{t=1}^{L_p} (x_t + y_t) \leq 1, \tag{2.2b}$$

$$x_t \in \{0,1\}, \qquad \forall t = \{1,2,...,L_p\}, \tag{2.2c}$$

$$y_t \in \{0,1\}, \qquad \forall t = \{1,2,...,L_p\}, \tag{2.2d}$$

where L_p denotes the platform lifetime.

2.2.1 Objective value modeling

In the following, we elaborate on how CA, GHG emissions, and NPV are calculated. Table 2.2 summarizes the nomenclature used.

Competitive advantage

We assume that the value of CA in the floating offshore wind industry stems from first-mover advantages and economies of scale. Early entry into emerging industries tends to yield higher market shares and CA (Miller et al., 1989). We consider the advantage obtained from early entry to be directly related to the investment timing. Furthermore, economies of scale may yield significant advantages. In the offshore wind industry, economies of scale are mainly obtained by increasing the rated power of projects (International Energy Agency, 2019a). As we assume that the OWF covers a fixed portion of the platform's energy demand, the rated power is

[4] A Bermuda option is an American option that can be exercised at predetermined discrete points of time. In our case, the decision of whether to exercise is revisited once a year.

predetermined by factors outside the operator's control and incorporated into the scaling constant s_3 from (2.1). Hence, the value of CA is modeled solely as a function of the investment timing:

$$\text{CA} = \sum_{t=1}^{5} \frac{x_t}{2^{(t-1)}}. \tag{2.3}$$

The monetary value of CA is s_3 if the operator undertakes investment in the OWF of required size immediately. For simplicity, we assume the CA to be halved for each year investment is postponed until the fifth year. From there on, the number of participants in the market is considered large enough to erase any potential early-mover advantages. This assumption is based on the fact that several energy companies and developers of significant size have stated interest in developing large-scale floating OWFs on the NCS in the near future (Torbjørnsdal, 2020; Aker Offshore Wind, 2021; Equinor, 2021a; Haugaland Vekst, 2021; Renewables Now, 2021).

Table 2.2: The nomenclature used in this paper.

Nomenclature	Description	Unit
cf	Capacity factor of the OWF	-
CF_t	Cash flow in year t	[NOK]
CT_{OWF}	Construction time of the OWF	[Years]
CT_{PFS}	Construction time of the PFS solution	[Years]
d	Enova subsidy given to the OWF	-
Δ_{NOx}	Annual increase of the NOx tax	[NOK/(kg NOx·year)]
e	Total GHG emissions per unit of natural gas burned	[kg CO_2-eq./Sm^3]
e_{CO_2}	CO_2 emissions per unit of natural gas burned	[kg CO_2/Sm^3 gas]
e_{NOx}	NOx emissions per unit of natural gas burned	[kg NOx/Sm^3 gas]
E_p	Annual platform energy demand	[TWh]
f_{OWF}	Fraction of annual platform energy demand covered by the OWF	-
HHV_{gas}	Higher heating value of natural gas	[MJ/Sm^3]
I_t	Total investment cost incurred in year t	[NOK]
$I_{OWF,t}$	Present value of costs related to the OWF in year t	[NOK]
I_{PFS}	PFS investment cost	[NOK]
$K_{NOX\text{-}F}$	NOx Fund subsidy	[NOK/kg NOx]
l	Reduction in levelized cost of energy of floating OWFs until 2030	-
L_{OWF}	Lifetime of the OWF	[Years]
L_p	Remaining platform lifetime	[Years]
$NG_{cons,t}$	Natural gas burned in year t to power the platform	[Sm^3]
η_{gt}	Gas turbine efficiency	-
η_{PFS}	PFS efficiency	-
OM	Reduced annual operation and maintenance costs obtained by investment in PFS	[NOK]
$P_{el,t}$	Price of electricity in year t	[NOK/MWh]
$P_{EUA,t}$	Price of European Union allowances in year t	[NOK/kg CO_2]
$P_{gas,t}$	Contribution margin of natural gas in year t	[NOK/Sm^3]
r	Discount rate used by the NOx Fund	-
ρ	The operator's discount rate	-
s_2	Scaling constant for GHG emissions	[NOK/kg CO_2-eq.]
s_3	Scaling constant for CA	[NOK]
S_t	Subsidy received in year t	[NOK]
T	The last year where Enova awards subsidies to floating OWFs	-
τ_t	Total taxes paid in year t	[NOK]
$\tau_{CO_2,t}$	Norwegian tax on CO_2 emissions in year t	[NOK/kg CO_2]
τ_{NOx}	Initial tax on NOx emissions	[NOK/kg NOx]
Υ_{CO_2}	The Norwegian government's tax floor on CO_2 emissions from 2030 on	[NOK/kg CO_2]
w_1	Weight assigned to the NPV-objective	-
w_2	Weight assigned to the GHG-objective	-
w_3	Weight assigned to the CA-objective	-
x_t	Decision variable equal to 1 if investment in the OWF is pursued in year t, 0 otherwise	-
y_t	Decision variable equal to 1 if investment in PFS is pursued in year t, 0 otherwise	-

Greenhouse gas emissions

The GHG emissions are proportional to the volume of natural gas burned to power the platform, and represented by

$$\text{GHG} = \left(\sum_{t=1}^{L_p} \text{NG}_{\text{cons,t}}\right) \cdot e, \tag{2.4}$$

where $\text{NG}_{cons,t}$ denotes the natural gas burned to power the platform in year t.

$$\text{NG}_{\text{cons,t}} = \frac{E_p \cdot 3.6 \cdot 10^9}{\eta_{gt} \cdot HHV_{gas}} \cdot \left(1 - \sum_{i=1}^{t-CT_{OWF}} f_{OWF} \cdot x_i - \sum_{j=1}^{t-CT_{PFS}} y_j + \sum_{k=1}^{t-L_{OWF}} f_{OWF} \cdot x_k\right), \tag{2.5}$$

where the first term is the volume of gas needed to fully power the platform. The second term deducts the fraction, f_{OWF}, of gas burned if the platform is powered by the OWF in year t, while the third term ensures no gas is consumed if the platform is powered by PFS. Finally, the fourth term cancels out with the second if the OWF has been decommissioned by year t. GHG emitted from other activities than the platform power supply is unaffected by the decision and not included in the objective value.

Net present value

The final objective is to maximize the NPV. The NPV is given by the sum of expected future discounted cash flows,

$$NPV = \sum_{t=1}^{L_p} \frac{CF_t}{(1+\rho)^t}. \tag{2.6}$$

The cash flow in year t is given by

$$CF_t = -\frac{P_{EL,t} \cdot E_p \cdot 10^6}{\eta_{PFS}} \sum_{i=1}^{t-CT_{PFS}} y_i - P_{gas,t} \cdot NG_{cons,t} - I_t + S_t - \tau_t + OM \sum_{j=1}^{t-CT_{PFS}} y_j. \tag{2.7}$$

The first term on the right-hand side signifies the cost of purchasing electricity when a PFS solution is active. The second term covers the lost profit contribution from burning gas instead of selling it. The third and fourth terms represent investment costs and subsidies received, respectively. The final two terms account for the taxes paid and the reduction in gas turbine operating and maintenance costs when a PFS solution is chosen. In the following equations, we further decompose each of these terms into base parameters and decision variables.

$$I_t = y_t \cdot I_{PFS} + x_t \cdot I_{OWF,t}, \tag{2.8}$$

$$\begin{aligned} S_t = x_t \cdot d \cdot \mathbb{1}_{t \le T} \cdot I_{OWF,t} + \frac{E_p \cdot e_{NOx} \cdot K_{NOX-F} \cdot 3.6 \cdot 10^9}{\eta_{gt} \cdot HHV_{gas}} \\ \cdot \left(x_t \sum_{i=t+CT_{OWF}}^{min(t+CT_{OWF}+L_{OWF},L_p)} \frac{f_{OWF}}{(1+r)^{i-t}} + y_t \sum_{j=t+CT_{PFS}}^{L_p-t} \frac{1}{(1+r)^{j-t}} \right), \end{aligned} \tag{2.9}$$

$$\tau_t = \text{NG}_{\text{cons,t}}(e_{NOx}(\Delta_{NOx} \cdot t + \tau_{NOx}) + e_{CO_2}(\tau_{CO_2,t} + P_{EUA,t})). \tag{2.10}$$

Any costs and revenues that are independent of the power source are not impacted by the operator's decision. As we aim to compare alternatives for platform power supply, such costs and revenues are ignored when modeling the objective value. This includes costs and revenues from other O&G-related operations, such as oil sales or extraction costs.

2.2.2 Stochastic state variables

Some of the input variables vary considerably on a daily, monthly, and yearly basis. This applies to the internal gas price of the operator[5], the European Union allowances (EUA) price, and the electricity price. Their development in recent years is illustrated in Figure 2.2. Due to the uncertainty of future prices, we choose to use stochastic processes to model these variables. Specifically, we assume that the internal gas price (i=gas), EUA price (i=EUA), and electricity price (i=el) follow geometric Brownian motions (GBM) given by

$$dP_{i,t} = \mu_i P_{i,t} dt + \sigma_i P_{i,t} dW_t, \tag{2.11}$$

where W_t is Brownian motion, t is the year, σ_i the volatility and μ_i the drift of the price $P_{i,t}$, where i $\in$ {el,EUA,gas} (McDonald, 2013).

As we consider a time horizon of several decades, it is primarily the long-term variations of the variables that affect the optimal decision. Accordingly, short-term fluctuations are less relevant in such a context, as pointed out by Schwartz (1998) and Pindyck (1999). Pindyck (1999) argues that the mean-reversion rate of energy prices is slow and that their volatility is stable across time. Therefore, he concludes that a GBM is unlikely to lead to significant errors in the optimal investment decision when large time horizons are considered. Schwartz (1998) presents similar findings and argues that a GBM is an acceptable approximation for how prices evolve over the long term. For these reasons, we consider GBMs to be satisfactory approximations. This is a common assumption made when modeling commodity price processes in the ROs literature. For example, Siddiqui and Marnay (2008) and Siddiqui and Maribu (2009) use a GBM to model natural gas prices, Gollier et al. (2005), Fleten et al. (2007), Siddiqui and Fleten (2010), and Boomsma et al. (2012) to model electricity prices, and Tian et al. (2017) and Li et al. (2018) to model carbon tax prices.

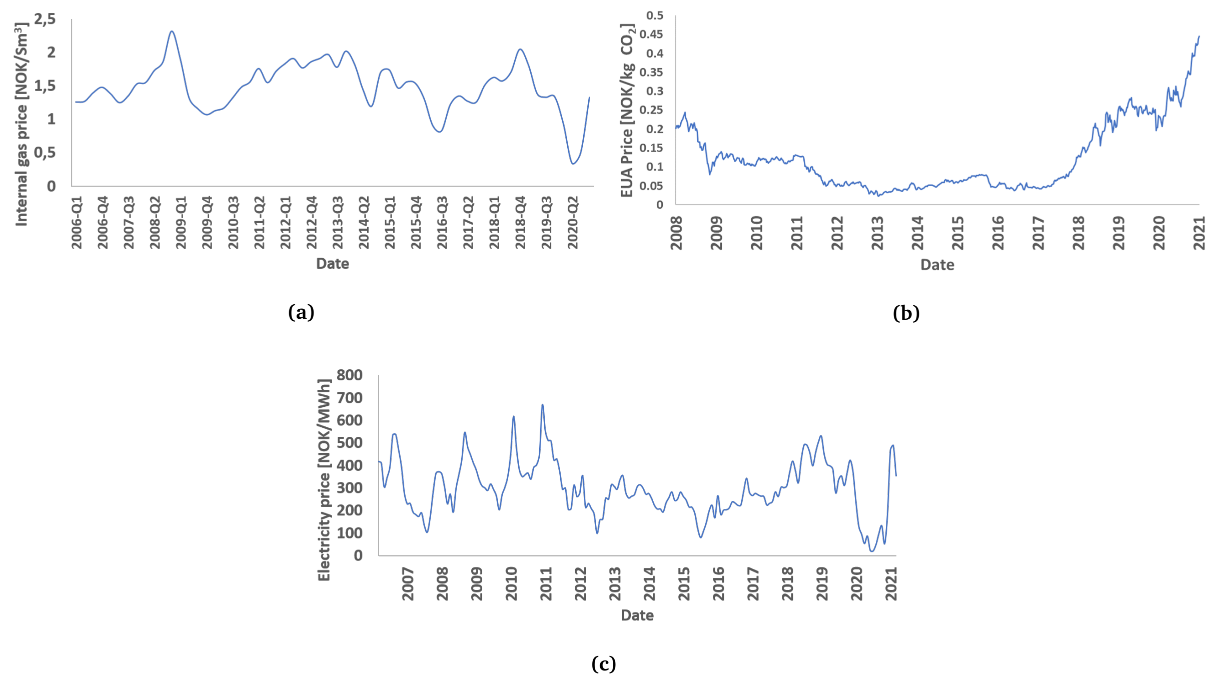


Figure 2.2: The development in recent years of (a) the internal gas price of Equinor[6] (Equinor, 2020a), (b) the EUA price (EMBER, 2021), and (c) the Norwegian electricity price (Nord Pool, 2021).

[5]The internal gas price is the sales price of gas deducted for costs related to gas transport to market and a marketing fee element (Equinor, 2020a). In other words, it is the contribution margin of natural gas after production.

2.2.3 Solution approach

In this paper, we apply LSM to find the optimal investment strategy to the operator's decision problem. In order to evaluate the optimal exercise strategy of ROs, dynamic programming (DP) is typically required to capture the value of future learning and decision-making. However, DP suffers from the curse of dimensionality and rapidly becomes intractable for complex real-world problems. One of the main difficulties when applying DP is the computation of the expected continuation value (Powell, 2009). LSM approximates the DP approach by using least squares regression to estimate the conditional continuation value at each point in time. Although LSM is an approximation of the optimal DP-solution, it has been shown to give near-optimal results (Longstaff and Schwartz, 2001). Furthermore, it is particularly useful for problems where several state variables influence the decision, such as in our case. This is due to the fact that the computational requirement only increases linearly with the addition of variables. Other methods such as finite difference and lattice-based approaches greatly suffer from dimensionality in such problems. For this reason, LSM is often perceived as a more suitable method for solving ROs problems with multiple state variables (Stentoft, 2004).

As defined by Longstaff and Schwartz (2001), the LSM algorithm is initiated by simulating ω paths for the stochastic variables. Hence, we generate ω paths for the evolution of electricity prices, internal gas prices, and EUA prices over time. The prices in each path are denoted as $P^{\omega}_{el,t}$, $P^{\omega}_{gas,t}$ and $P^{\omega}_{EUA,t}$, respectively. The LSM algorithm provides a decision rule that maximizes the value of the option to invest in either PFS or the OWF at each discrete time step t. At each time step and for every path ω where

$$\psi_{\omega}(x_{t,\omega}=1,y_{t,\omega}=0)>\psi_{\omega}(\vec{x}_{t,\omega}=\vec{0},\vec{y}_{t,\omega}=\vec{0})\vee\psi_{\omega}(x_{t,\omega}=0,y_{t,\omega}=1)>\psi_{\omega}(\vec{x}_{t,\omega}=\vec{0},\vec{y}_{t,\omega}=\vec{0}), \quad (2.12)$$

the value of exercising the options is compared to the expected conditional continuation value. Only paths where (2.12) holds are considered as the decision to exercise is not relevant if both options are out of the money[7]. The decision variables for each path, $x_{t,\omega}$ and $y_{t,\omega}$, are chosen to maximize the value of the option, $\xi_{\omega}(x_{t,\omega},y_{t,\omega})$ for all ω, where

$$\xi_{\omega}(x_{t,\omega},y_{t,\omega})=\begin{cases}\psi_{\omega}(x_t=x_{t,\omega},y_t=y_{t,\omega}) & \text{if } x_{t,\omega}=1\vee y_{t,\omega}=1,\\ E[Y_{t,\omega}|\vec{P}^{\omega}_t] & \text{if } x_{t,\omega}=y_{t,\omega}=0.\end{cases} \quad (2.13)$$

Hence, the optimal investment strategy for each path at time t is decided by

$$\max_{x,y} \quad \xi_{\omega}(x_{t,\omega},y_{t,\omega}) \quad (2.14a)$$

$$\text{subject to} \quad x_{t,\omega}+y_{t,\omega}\leq 1, \quad (2.14b)$$

$$x_{t,\omega}\in\{0,1\}, \quad (2.14c)$$

$$y_{t,\omega}\in\{0,1\}. \quad (2.14d)$$

$\psi_{\omega}(x_t=1,y_t=0)$ represents the exercise value of the option to invest in the OWF at time t for path ω, while $\psi_{\omega}(x_t=0,y_t=1)$ is the exercise value of the option to invest in PFS. $E[Y_{t,\omega}|\vec{P}^{\omega}_t]$ denotes the expected conditional continuation value at time t for path ω. $\vec{P}^{\omega}_t$ includes the prices $P^{\omega}_{i,t}$ in path ω where i ∈ {el,EUA,gas}.

LSM works recursively and first compares the value of exercising the options with the continuation value at the end of the platform's lifetime. At this time step, the continuation value is known, as the options yield zero value after the platform is decommissioned. Therefore, we set $t=L_p$ and $E[Y_{L_p,\omega}|\vec{P}^{\omega}_{L_p}]=0$ and solve (2.14a)-(2.14d) for all ω paths to find the optimal investment strategy at the end of the platform's lifetime. Next, the algorithm recurses to the preceding time step where the operator considers investing, the previous year. As $t=L_p-1$, the expected conditional continuation value is unknown and must be determined in order to evaluate whether the investment opportunities should be pursued. Gamba (2003) expands the LSM algorithm to handle mutually exclusive options by finding that the expected continuation value depends solely on the optimal investment strategy at future time steps. This strategy is known as the algorithm works recursively,

[6]Equinor is the largest operator on the NCS (Norwegian Ministry of Petroleum and Energy, 2020a).

[7]For this problem, the options are out of the money if the objective value obtained by investment is smaller than the objective value obtained by never investing.

and the value can be approximated through least squares regression. The expected continuation value is a function of the three stochastic state variables, such that

$$E[Y_{t,\omega}|\vec{P}_t^{\omega}] = f(P_{gas,t}^{\omega}, P_{el,t}^{\omega}, P_{EUA,t}^{\omega}). \tag{2.15}$$

In general, the basis function f should include terms of all state variables and their cross-products (Longstaff and Schwartz, 2001). As this paper aims to provide relevant information for the operator's decision, we do not assess different basis functions searching for the optimal option. We choose the function that includes as much information as possible without significantly reducing computational speed. Accordingly, we let f consist of two terms per price, as well as all cross-products of the prices. Longstaff and Schwartz (2001) and Moreno and Navas (2003) conclude that, in general, the LSM algorithm is robust to the choice of basis function. Hence, although our choice of f may be overly complex for this decision problem, it should lead to a satisfactory level of accuracy without impeding computational speed. The approximated conditional continuation value is given by

$$\begin{aligned} E[Y_{t,\omega}|\vec{P}_t^{\omega}] = \alpha + \beta_1 P_{gas,t}^{\omega} + \beta_2 (P_{gas,t}^{\omega})^2 + \gamma_1 P_{el,t}^{\omega} + \gamma_2 (P_{el,t}^{\omega})^2 + \epsilon_1 P_{EUA,t}^{\omega} \\ + \epsilon_2 (P_{EUA,t}^{\omega})^2 + \theta_1 P_{gas,t}^{\omega} P_{el,t}^{\omega} + \theta_2 P_{gas,t}^{\omega} P_{EUA,t}^{\omega} + \theta_3 P_{el,t}^{\omega} P_{EUA,t}^{\omega} + \phi P_{gas,t}^{\omega} P_{el,t}^{\omega} P_{EUA,t}^{\omega}, \end{aligned} \tag{2.16}$$

where the Greeks are regression coefficients found through least squares regression.

Once an expression for the expected continuation value is obtained, we can identify the optimal decision at the current time step for every path by inserting $E[Y_{t,\omega}|\vec{P}_t^{\omega}]$ into (2.14a)-(2.14d). When the decision has been made for all ω paths, we move another time step backward and repeat until $t = 1$ is reached. For every time step, a new regression is performed to find the appropriate coefficients at that point in time. This leads the continuation value to take into account all information available regarding future decisions at each time step.

Figure 2.3 illustrates the steps of the presented algorithm. The input consists of the objective value modeling from Section 2.2.1 and the stochastic processes defined in Section 2.2.2. The first step is Monte Carlo simulations for the stochastic variables. Second, the optimal decision at maturity is chosen. Third, the algorithm recurses backward to the previous year, and least squares regression based on the paths in the money is performed. The next step is to select the optimal decision at $t = L_p - 1$. Finally, the algorithm continues to recurse backward while $t > 1$. The output from the LSM algorithm is both the frequency of how often to invest in the different alternatives and the optimal decision timing for each path. Additionally, the total value of the option to invest in electrification alternatives is calculated. We use MATLAB (2020) to implement the LSM approach.

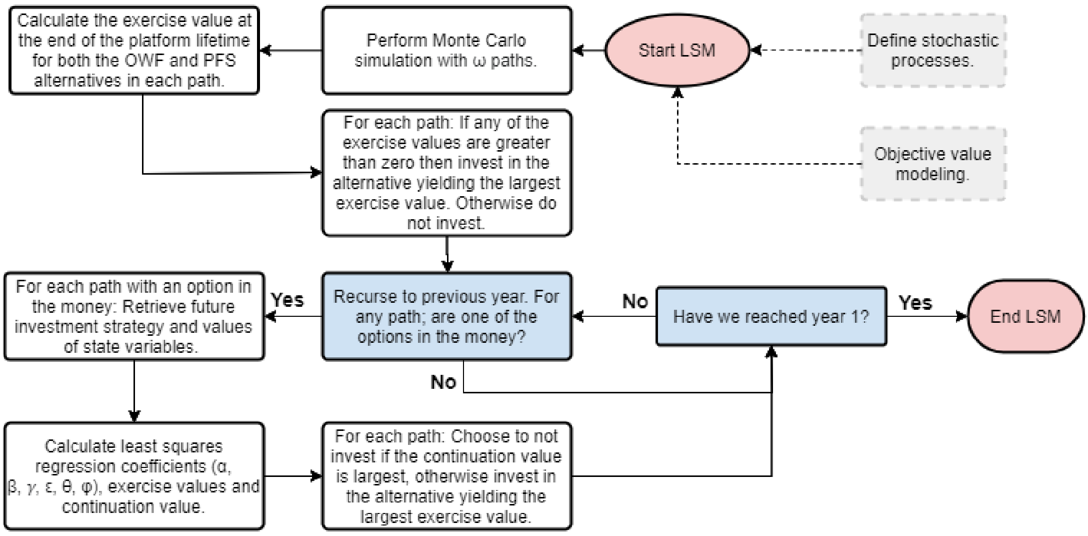


Figure 2.3: The LSM algorithm as used in this paper. White boxes represent calculation nodes, blue boxes indicate decision nodes, and grey boxes represent preceding modeling steps.

Chapter 3

Data

In this chapter, we elaborate on the parametrization of parameter values for our representative case. First, we present characteristics of operational O&G fields on the NCS to determine realistic conditions for the operator. Next, we summarize and discuss the assumptions and parameter values for the base case. Finally, we estimate the process parameters relevant to the stochastic state variables.

3.1 Oil and gas fields on the Norwegian continental shelf

The NCS is defined as the total sea area under Norwegian jurisdiction and amounts to $2,039,951$ km^2. All 100 active Norwegian O&G fields[8] are located on the continental shelf (Norwegian Petroleum Directorate, 2021a). The fields can be grouped into five clusters based on location: Barents Sea, Norwegian Sea, Northern North Sea, Central North Sea, and Southern North Sea. The clusters are shown in Figure 3.1a. Table 3.1 summarizes the number of fields, years of production, water depth, and distance from shore for the clusters mentioned above. The distance from shore varies between approximately 50 km and 330 km, while ocean depth varies between 65 m and 1,270 m.

Table 3.1: The number of active fields, water depth, distance from shore, and years of production, for O&G fields located in the different clusters of the NCS (Norwegian Petroleum Directorate, 2021a). The distance from shore is measured from the oil field to its main onshore supply base. We denote new fields as fields where production has yet to start or has started within the last five years.

		Water depth [m]			Distance from shore [km]			Years of production	
Area	**Active fields**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**	**New fields**
Barents Sea	3	370	325	390	142	86	243	5	2
Norwegian Sea	24	355	220	1,270	207	110	279	10	8
Northern North Sea	32	235	95	400	138	53	260	20	5
Central North Sea	28	115	70	130	197	140	242	13	8
Southern North Sea	13	70	65	72	292	255	331	20	3

3.2 Assumptions and platform characteristics

Table 3.2 summarizes all base-case parameter values. The values mainly originate from government reports and data sources such as Statistics Norway (2017), Norwegian Ministry of Climate and Environment (2020), Norwegian Petroleum Directorate et al. (2020), and The Norwegian Water Resources and Energy Directorate (2020), as well as from technological insights provided by corporate documents and presentations, in particular ABB (2015) and Equinor (2021c). Further justification for the values chosen will be provided upon request. In the following, we elaborate on modeling assumptions supporting base-case parametrization.

As we aim to study an investment decision from the perspective of an O&G operator, we develop a representative case to capture realistic conditions for a platform on the NCS. In the base case, we consider a hypothetical

[8] We denote active fields as fields that are currently producing, or approved for production.

platform located in the Norwegian Sea as there are numerous new fields in this cluster. Furthermore, we let the water depth and distance from shore correspond to the median values in this cluster, 355 m and 207 km, respectively. The remaining platform lifetime is expected to be 35 years, and the platform is assumed to have a fixed annual power demand of 0.3 TWh. This power demand corresponds to a medium-sized platform, such as the one operating the Draugen field, also located in the Norwegian Sea (Norwegian Petroleum Directorate et al., 2020). In reality, platform energy demand may vary from year to year due to changes in production profile and field composition. However, for simplicity, we assume constant power consumption throughout the platform's lifetime. Currently, power is supplied by gas turbines with an efficiency of 32%, slightly higher than the average efficiency of turbines on the NCS in 2008 (31.4%) (Norwegian Petroleum Directorate et al., 2008). Recent research suggests that only minor improvements to efficiency have been achieved since then, and we consequently consider 32% to be an appropriate assumption (Vandenbussche et al., 2021).

Table 3.2: The parameter values used in the base case.

Parameter	Description	Base-case value	Data source
cf	Capacity factor of the OWF	40%	(The Norwegian Water Resources and Energy Directorate, 2020)
CT_{OWF}	Construction time of the OWF	2 years	(Equinor, 2021c)
CT_{PFS}	Construction time of the PFS solution	2 years	(Equinor, 2020b)
d	Enova subsidy given to the OWF	30%	(Enova SF, 2020)
Δ_{NOx}	Annual increase ofthe NOx tax	2 NOK/kg NOx	(The Business Sector's NOx Fund, 2020)
e	GHG emissions per unit of natural gas burned	2.364 kg CO2-eq./Sm^3	(Norwegian Environment Agency, 2020b)
e_{CO_2}	CO_2 emissions per unit of natural gas burned	2.34 kg CO_2/Sm^3	(Statistics Norway, 2017)
e_{NOx}	NOx emissions per unit of natural gas burned	0.00627 kg NOx/Sm^3	(Statistics Norway, 2017)
E_p	Annual platform energy demand	0.3 TWh	(Norwegian Petroleum Directorate et al., 2020)
f_{OWF}	Platform energy demand covered by the OWF	35%	(Norwegian Petroleum Directorate et al., 2020)
HHV_{gas}	Higher heating value of natural gas	40 MJ/Sm^3	(The Norwegian Water Resources and Energy Directorate, 2004)
I_{OWF}	Present value of costs related to the OWF in year 1	1,950 million NOK	(Equinor, 2021c)
I_{PFS}	PFS investment cost	2,500 million NOK	(ABB, 2021)
$K_{NOX\text{-}F}$	NOx Fund subsidy	50 NOK/kg NOx	(The Business Sector's NOx Fund, 2018)
l	Reduction in LCOE of floating OWFs until 2030	10% every 3^{rd} year	(Eik, 2018)
L_{OWF}	Lifetime of the OWF	25 years	(THEMA Consulting Group, 2020)
L_p	Remaining platform lifetime	35 years	(Norwegian Petroleum Directorate, 2020)
η_{gt}	Gas turbine efficiency	32%	(Norwegian Petroleum Directorate et al., 2008)
η_{PFS}	PFS efficiency	90%	(ABB, 2015)
OM	Reduced operation and maintenance costs by PFS	15 million NOK	(Norwegian Petroleum Directorate et al., 2008)
r	Discount rate used by the NOx Fund	7%	(The Business Sector's NOx Fund, 2018)
ρ	The operator's discount rate	7%	(Norwegian Petroleum Directorate et al., 2020)
s_2	Scaling constant for GHG emissions	0.1 NOK/kg CO_2-eq.	
s_3	Scaling constant for CA	200 million NOK	
T	Final year of Enova subsidies to floating OWFs	8	(Enova SF, 2020)
τ_{CO_2}	Norwegian CO_2-tax in 2021 (year 0)	0.55 NOK/kg CO_2	(Norwegian Ministry of Finance, 2020)
τ_{NOx}	NOx tax in 2021 (year 0)	16.5 NOK/kg NOx[9]	(The Business Sector's NOx Fund, 2020)
Υ_{CO_2}	Tax floor on CO_2 emissions from 2030 on	2 NOK/kg CO_2	(Norwegian Ministry of Climate and Environment, 2020)
w_1	Weight assigned to the NPV-objective	0.7	
w_2	Weight assigned to the GHG-objective	0.15	
w_3	Weight assigned to the CA-objective	0.15	

For the electrification alternatives, the OWF is assumed to have a lifetime of 25 years, while the PFS solution is assumed to last for the duration of the platform lifetime. As the platform energy demand is 0.3 TWh per year, the power rating of the PFS-cable must be at least equal to

$$Q_{PFS} = \frac{E_p \cdot 10^{12}}{8760 \cdot \eta_{PFS}} \approx 38 \text{ MW}. \tag{3.1}$$

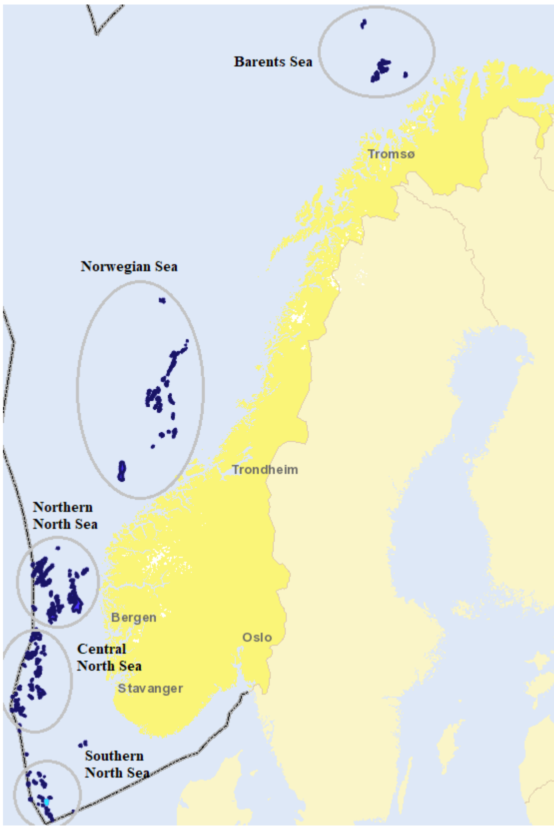
To ensure the security of electricity supply, we assume an appropriate PFS cable to have a rated power of 40 MW. The investment cost of a PFS solution with cable length 207 km and power rating 40 MW is approximately 2,500 million NOK (ABB, 2021). This assumes that only minimal modifications to the platform and its electrical infrastructure are required to accommodate PFS.

The rated power of the OWF is given by

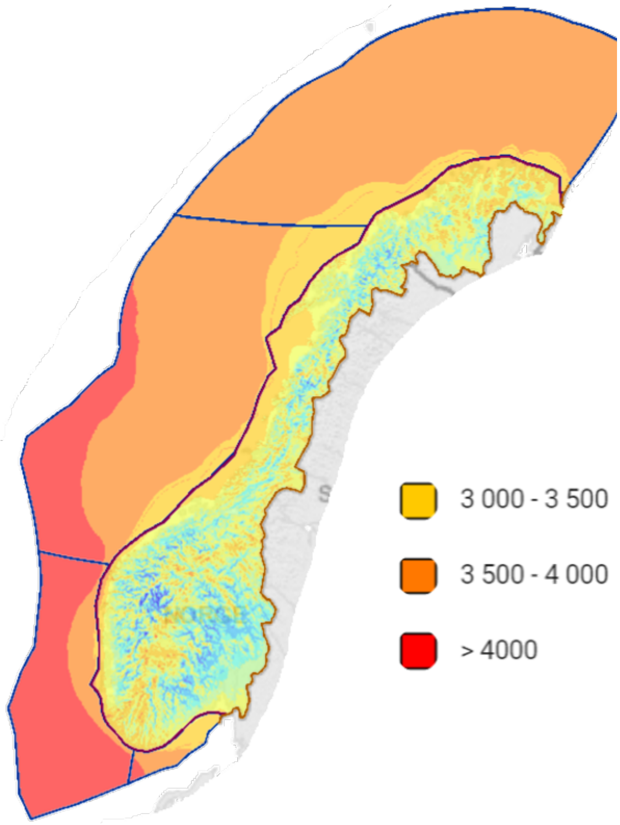
$$Q_{OWF} = \frac{f_{OWF} \cdot E_p \cdot 10^{12}}{8760 \cdot cf} \approx 30 \text{ MW}. \tag{3.2}$$

[9]As most Norwegian O&G companies partake in the NOx Agreement, we assume that our operator is also a participant. Partaking in the NOx Agreement allows him to pay a reduced tax on NOx emissions of 16.5 NOK/kg by committing to reduce emissions. In comparison, the standard Norwegian NOx tax is 23.48 NOK/kg NOx (Norwegian Ministry of Petroleum and Energy, 2020b; The Business Sector's NOx Fund, 2020).

This rating stems from a partial power supply of 35%, identical to the expected power supply provided by Hywind Tampen, and a capacity factor[10] of 40%. This value represents a conservative estimate, as most of the NCS have wind characteristics yielding factors above 40%, as shown in Figure 3.1b (The Norwegian Water Resources and Energy Directorate, 2020). The present value (PV) of costs related to a 30 MW off-grid floating OWF is approximately 1,950 million NOK (Equinor, 2021c).



(a)



(b)

Figure 3.1: (a) The different clusters of O&G fields on the NCS (Norwegian Petroleum Directorate, 2021b). (b) The capacity factor on the NCS multiplied by 8760 h. A capacity factor of 40% corresponds to values of approximately 3,500 in the figure. The values assume a wind turbine height of 120 m above sea level (The Norwegian Water Resources and Energy Directorate, 2020).

Floating offshore wind is an immature technology, and significant cost reductions are expected over the next ten years (Wind Europe, 2017). Equinor expects a reduction of 50-60% of the levelized cost of energy[11] (LCOE) by 2030. Such reductions can be achieved by developing new floating OWFs of increasing size every third year, with a 20-25% reduction of the LCOE per size increment. 5-15 percentage points are due to supply chain and technology development, while the rest is due to scale effects (Eik, 2018). As the OWF the operator considers investing in is of fixed size, we neglect LCOE reductions due to scale effects. Hence, we assume the LCOE to diminish by 10% every third year until year 10. This leads the PV of all costs incurred by investing in the OWF in year t to be equal to

$$I_{OWF,t} = \begin{cases} I_{OWF}(1-l\cdot\frac{t-1}{3}) & \text{for } t\in[1,4], \\ I_{OWF}(1-l)(1-l\cdot\frac{t-4}{3}) & \text{for } t\in[5,7], \\ I_{OWF}(1-l)^2(1-l\cdot\frac{t-7}{3}) & \text{for } t\in[8,10], \\ I_{OWF}(1-l)^3 & \text{for } t\in[11,L_p], \end{cases} \tag{3.3}$$

[10]The capacity factor for wind power is defined as the total energy generated per year, divided by the rated power of the wind turbine (International Energy Agency, 2019a).

[11]The levelized cost of energy is defined as the net present cost of energy generation over a unit's lifetime.

where a linear decrease in costs is assumed within the three-year intervals.

Generally, costs related to OWFs are dominated by capital expenditures (CAPEX). For Hywind Tampen, CAPEX represents 75% of the expected PV of costs. Hywind Tampen received subsidies from Enova covering 46% of the investment cost (Winje et al., 2019; Equinor, 2021c). As one of the criteria for receiving Enova support is the development of new technologies that lead to cost reductions and innovation, the project received significant support due to being the first in Norway (Enova SF, 2019). We assume the subsidy level given to the operator to be slightly lower at 40% of CAPEX. This reduction is due to the fact that the innovative contribution is smaller as a similar floating OWF already exists in Hywind Tampen. Further, we assume a similar cost structure as Hywind Tampen, leading the subsidy to cover 30% of the PV of all costs. The subsidy is obtainable for investments made in year 8 (2029) at the latest, as we assume floating wind to have reached a level of maturity that prevents subsidies from 2030 on.

The Norwegian government announced in 2021 that they plan to set a floor on the combined carbon[12] (CC) tax of 2 NOK/kg CO_2 emitted from 2030 on (Norwegian Ministry of Climate and Environment, 2020). We assume that this price floor will be enacted. Thus, the combined value of EUA price and national carbon tax is at least 2 NOK/kg CO_2 from 2030 on. As the Norwegian government cannot alter the EUA price, the national tax will be adjusted to ensure that the target price is met. We assume that the national tax is adjusted according to the expected increase in the EUA price and the time remaining until 2030. Furthermore, the CC tax is modeled such that 2 NOK/kg CO_2 is not surpassed unless the EUA price exceeds this value. Hence, the national tax is given by

$$\tau_{CO_2,t} = \begin{cases} \tau_{CO_2} & \text{for t} = 1, \\ max(0, \tau_{CO_2,t-1} + \frac{\Upsilon_{CO_2} - \tau_{CO_2,t-1} - P_{EUA,t-1}}{9-t} - (E[P_{EUA,t} | P_{EUA,t-1}] - P_{EUA,t-1})) & \text{for t} \in [2,8] \cap \tau_{CO_2,t} + P_{EUA,t} \leq \Upsilon_{CO_2}, \\ max(0, \Upsilon_{CO_2} - P_{EUA,t}) & \text{for t} \in [2,8] \cap \tau_{CO_2,t} + P_{EUA,t} \geq \Upsilon_{CO_2}, \\ max(0, \Upsilon_{CO_2} - P_{EUA,t}) & \text{for t} \in [9, L_p]. \end{cases} \tag{3.4}$$

Figure 3.2 illustrates two example paths of the CC tax for different EUA price scenarios. The black lines represent a scenario where the EUA price exceeds the imposed tax floor by the Norwegian government. The blue lines represent a scenario where it never surpasses the floor such that the CC tax remains equal to 2 NOK/kg CO_2 from 2030 to the end of the platform's lifetime.

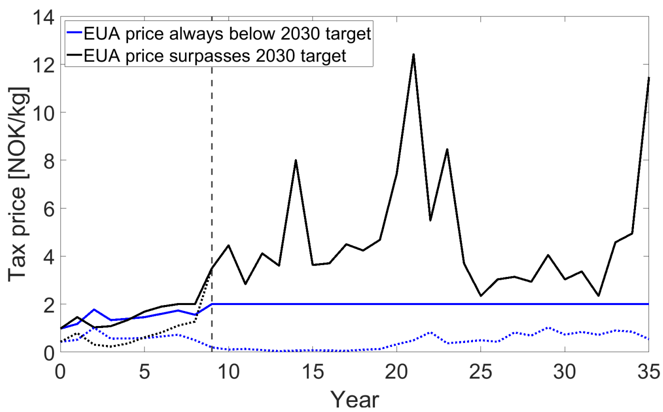


Figure 3.2: The evolution of the CC tax for two example paths of the EUA price. The solid lines represent the CC tax, while the dotted lines represent the EUA price. Black lines portray a path where the EUA price exceeds the imposed tax floor by the Norwegian government. Blue lines portray a path where it never surpasses the floor. The dashed vertical line indicates the year where the tax floor is imposed, 2030.

In addition to the exogenous parameters previously discussed, the objective value also depends on the weights and scaling constants that reflect the operator's preferences and beliefs. Accordingly, the operator must assign values to these parameters. He finds it unreasonable to weigh future profits or emission reductions strongly if that results in a disproportionally high risk of bankruptcy due to negative short-term NPV. Therefore, he

[12]The combined carbon tax consists of the Norwegian CO_2-tax and the EUA price.

considers maximizing NPV as the most important objective. At the same time, the objectives related to CA and GHG emissions remain significant to the operator in the long term, and he considers them of equal importance. Taking these preferences into consideration, he chooses to assign a weight of 0.7 to the NPV-objective, and 0.15 to the secondary objectives. Furthermore, the operator considers immediate investment in a 30 MW floating OWF to yield CA worth 200 million NOK, and 0.1 NOK/kg CO_2-eq. to be an appropriate penalty for emissions. Therefore, the scaling constants $s_2 = 0.1$ NOK/kg CO_2-eq. and $s_3 = 200$ million NOK.

3.3 Estimating price process parameters

In the following, we explain how we calibrate the parameter values of the price processes. Namely, the internal gas price, electricity price, and EUA price. To estimate the volatility parameter of the GBMs, we use the implied volatility of options on futures contracts. We do so because this represents the market's current belief of the underlying's volatility, in contrast to historical data. Black (1976) modifies the Black-Scholes option pricing model developed by Black and Scholes (1973) to price options on commodities and futures contracts. The fair prices of such options are given by

$$c_0 = (F \cdot N(d_1) - K \cdot N(d_2)) \cdot e^{-rT}, \tag{3.5}$$
$$p_0 = (-F \cdot N(-d_1) + K \cdot N(-d_2)) \cdot e^{-rT}, \tag{3.6}$$

where c_0 and p_0 is the price of a European call and put option, respectively, on a forward with price F, strike price K, and maturity T. r is the risk-free rate, $d_1 = \frac{ln(\frac{F}{K})+0.5\cdot\sigma^2\cdot T}{\sigma\sqrt{T}}$ and $d_2 = d_1 - \sigma\sqrt{T}$ with σ being the volatility of the underlying and N(x) being the cumulative standard normal distribution.

The implied volatility is then found by inserting F, K, r, and c_0/p_0 into (3.5)/(3.6). Once the implied volatility is calculated, the drift is found by applying Itô's lemma to solve (2.11). This yields

$$d\ln(P_t) = (\mu - \frac{\sigma^2}{2})dt + \sigma dW_t \longrightarrow \mu = E[\ln(\frac{P_t}{P_{t-1}})] + \frac{\sigma^2}{2}. \tag{3.7}$$

As the problem in this paper has a long time horizon, and the stochastic price processes are volatile, the simulated prices may become unreasonably high in some simulation paths. To avoid exorbitant prices we consider unreasonable, we introduce a price ceiling for all stochastic parameters. The ceiling prevents the prices from exceeding a specified threshold, such that

$$P_{i,t} = \min(P_{i,t-1}e^{\mu_i - 0.5\sigma_i^2 + \sigma_i W_t}, \overline{P_i}) \qquad \forall i \in \{\text{el,EUA,gas}\}, \tag{3.8}$$

where $\overline{P_i}$ is the ceiling of the price P_i. The maximum limit is chosen to be 100 times the historical maximum of the internal gas price and EUA price, while the maximum limit of the electricity price is 30,605 NOK/MWh, adhering to the limit set by the power exchange Nord Pool (2021). Table 3.3 summarizes the parameter values, the initial price, the ceiling, and the data sources that are used to estimate the volatility of the stochastic processes for the internal gas price, EUA price, and electricity price, respectively.

Table 3.3: GBM process parameter values, along with initial values, price ceilings, and sources used to estimate the process parameters.

	Year 0 value	$\overline{P_i}$	σ	μ	**Data source**
Internal gas price [NOK/Sm^3]	0.8	232	25%	1.25%	Options on West Texas Intermediate (WTI) futures[13] from CME Group (2021)
EUA price [NOK/kg]	0.43	50	43%	10.85% after 3 years[14]	Options on EUA futures from European Energy Exchange AG (2021)
Electricity price [NOK/MWh]	270	30,605	30%	6.66% after 2 years[14]	Options on Nordic power futures from Nasdaq (2021)

[13]As the internal gas price is not traded on the market, the WTI oil price is used as a spanning asset. On the NCS, natural gas is often traded on long-term contracts where the price follows fluctuations in the Brent Spot oil price. We assume the internal gas price to be perfectly correlated with the Brent Spot oil price. Furthermore, as options data on Brent futures is limited, the Brent Spot is assumed to be perfectly correlated with the WTI oil price.

[14]The drift of the EUA price (electricity price) is chosen such that the expected value of the price matches the forward curve in the first 3 (2) years.

Chapter 4

Results and discussion

In this chapter, we apply the methodology presented in Chapter 2 to find the optimal solution to the operator's decision problem. In the following, we first present the results for the base-case parameter set in Section 4.1. Next, we perform sensitivity analysis to highlight how changes in parameter values impact the operator's decision in Section 4.2. Finally, in Section 4.3, we examine what it takes to make the OWF the operator's preferred alternative.

4.1 Base case

Figure 4.1 presents the frequency of optimal alternatives and investment timing for one million paths generated with the base-case assumptions defined in Chapter 3. The optimal alternative and timing for each path are found by applying the LSM algorithm presented in Section 2.2.3. The result indicates that immediate investment in PFS is the optimal decision as it is the most frequently chosen combination of alternative and timing. Following the decision rule provided by the LSM algorithm, the investment opportunity has a value of 2.22 billion NOK. To understand how dominant immediate investment in PFS is compared to the other alternatives, the distribution of the operator's decision across all paths is plotted. PFS is the preferred alternative in most scenarios and is chosen in 63.8% of the paths. Investment in the OWF is chosen in only 10.0% of the cases, while for 26.3% of the paths, it is optimal for the operator to decline the investment opportunity and continue to power the platform by burning natural gas. When evaluating optimal timing, we find that immediate investment in PFS is the decision with the most occurrences (32.6%), while investing in year 8 is most frequent among paths where the OWF is optimal (1.1%). Year 1 is the preferred timing for PFS investments as its lifetime is at least as long as the platform lifetime. Therefore, investing as early as possible yields the most considerable reductions in gas consumption and incurred taxes. Year 8 is the most frequent timing for investments in the OWF as it is the year with the lowest net investment cost due to subsidies and reductions in the LCOE. Additionally, as internal gas prices and CC taxes are expected to increase, investment in year 8 will provide greater mitigation of future taxes and lost revenue from burning gas, relative to earlier investments.

To demonstrate the advantage of using a ROs approach, we compare the value obtained by following the LSM decision rule to that obtained by a greedy optimization algorithm[15]. Figure 4.2 shows the expected value of each alternative, calculated with a greedy optimization algorithm. The optimal solution is immediate investment in PFS, identical to the solution found using LSM. However, the expected value of always choosing PFS in year 1 is 2.00 billion NOK, 10% lower than the value obtained by following the LSM decision rule. Hence, for this decision problem, the value of future learning is significant as information obtained in the future may lead the operator to change his decision and realize a higher objective value. An interesting observation from the greedy optimization is that investment in the OWF prior to year 18 always yields a larger objective value than never investing. This suggests that it is always better to invest in the OWF than continuing to burn natural gas. Despite this, results obtained through the LSM algorithm suggest never investing in approximately a quarter of the paths. Although counter-intuitive, this is due to scenarios with large carbon taxes making

[15]The greedy optimization algorithm calculates the expected objective value obtained for each combination of alternative and timing, and chooses the solution that yields the largest value. The decision strategy is chosen prior to the first investment opportunity and does not incorporate the value of future learning.

investments in PFS yield significantly higher expected objective value than investments in off-grid floating OWFs. Therefore, there exist scenarios where the continuation value of PFS dominates the exercise value of the OWF, leading the operator to postpone investment while waiting for the exercise value of PFS to increase. If the increase fails to occur, the operator ends up never investing.

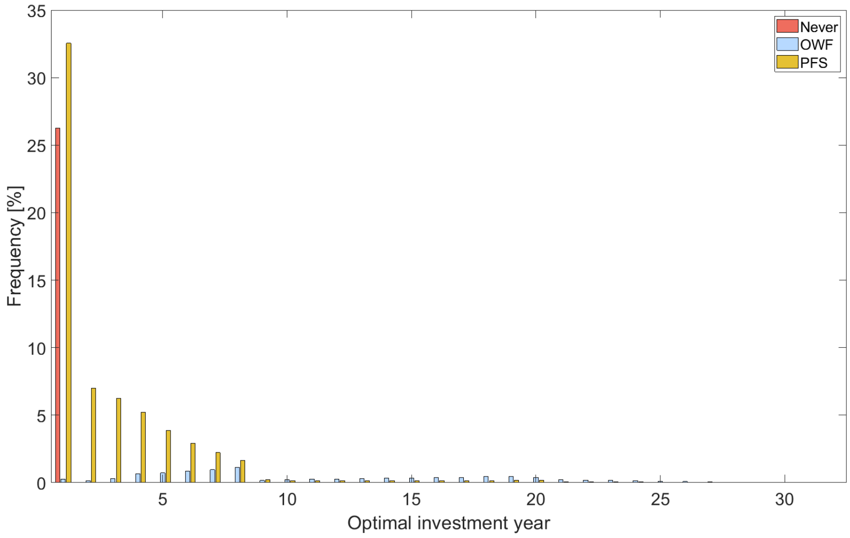


Figure 4.1: The LSM solution for the base-case problem. The bar chart presents the frequency of optimal alternatives. One million paths are generated.

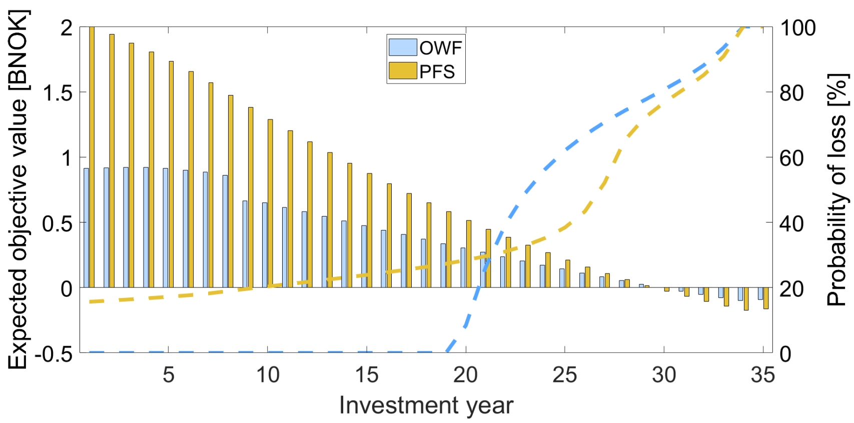


Figure 4.2: The greedy optimization solution for the base-case problem. The discounted expected objective value of electrification alternatives relative to never investing, as a function of the investment year (bars). The probability of investment in PFS (dashed yellow line) and the OWF (dashed blue line) yielding a lower objective value than the one resulting from never investing, as a function of the investment year. The algorithm utilizes the same paths used to find the LSM solution.

Figure 4.3 presents a scatter plot of optimal alternatives following the LSM decision rule as a function of mean electricity price and CC tax over the platform's lifetime. The plot indicates the decision thresholds between alternatives for different electricity prices and CC taxes. Within the circle in the bottom left corner, there is significant overlap between all alternatives. For such mean prices, the decision rule is highly dependent on how the prices evolve with time, not only their mean value. Figure 4.4 shows the distributions of optimal decisions within the region of overlap for each alternative, respectively. Individual scatter plots clearly showing all points for each alternative are appended in Appendix A. The results presented in Figure 4.3 indicate a clear pattern where a higher mean electricity price leads to investment in off-grid floating OWFs, while a higher mean CC tax leads to investment in PFS. Never investing occurs predominantly in scenarios with mean CC taxes below 4 NOK/kg CO_2. Even for these relatively low tax levels, the OWF is chosen when the electricity price is high. This is due to the fact that the expected value of PFS decreases with increasing electricity prices. This subsequently reduces the PFS continuation value, and the operator is more likely to invest in the OWF than to wait for the exercise value of PFS to increase. Finally, PFS dominates as long as the mean electricity price remains below 3,000 NOK/MWh. Our results suggest that, under base-case assumptions, the electricity price is defining for the operator's decision. As long as the electricity price remains moderate to low, PFS is almost always the chosen alternative.

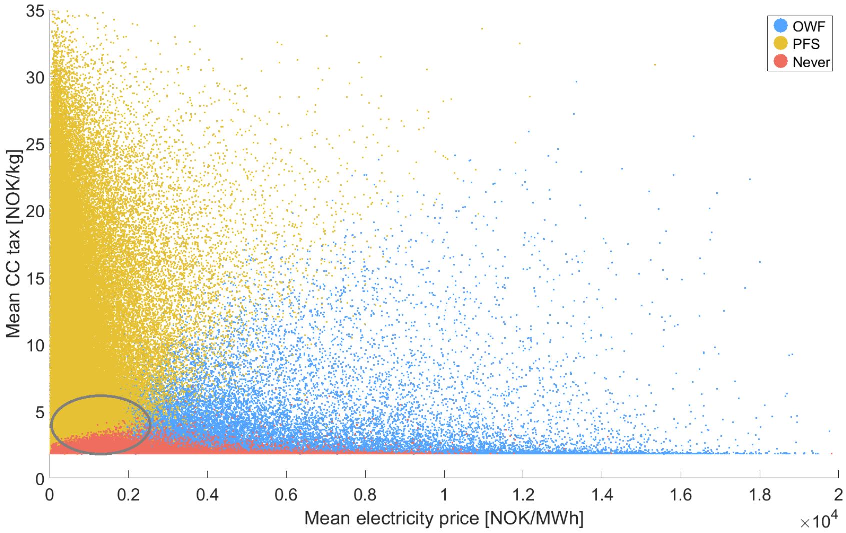
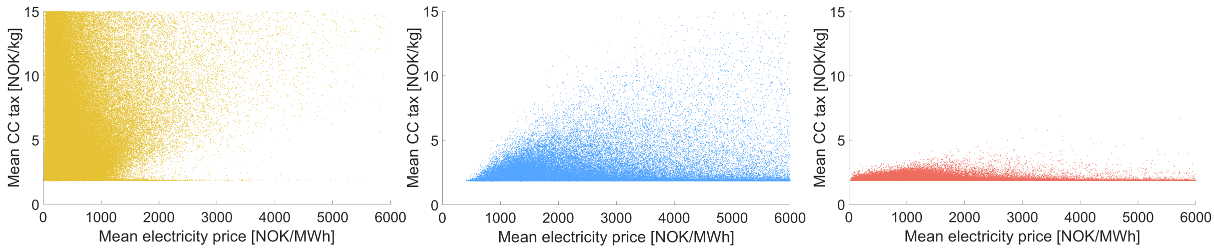


Figure 4.3: Scatter plot showing which alternative is optimal for the base-case paths when following the LSM decision rule as a function of mean electricity price and CC tax over the platform's remaining lifetime. The area encompassed by the circle has significant overlap between all three alternatives. Within this area, numerous blue dots are concealed by yellow and red dots. Similarly, yellow dots are concealed by red dots.



(a) (b) (c)

Figure 4.4: Scatter plots showing the base-case paths where the operator chooses: (a) PFS, (b) OWF, and (c) to never invest, when following the LSM decision rule as a function of mean electricity price and CC tax over the platform's remaining lifetime. Only paths that are within the overlapping region are included.

4.2 Sensitivity analysis

Our findings presented in Section 4.1 suggest that PFS is the preferred alternative for an operator under the base-case assumptions. To understand how the operator's decision is affected by changes in parameter values, we perform a sensitivity analysis. Table 4.1 gives an overview of the results from the sensitivity analysis. The table illustrates the impact of altering parameter values on investment timing and the frequency of alternatives chosen. Upward (downward) pointing arrows represent frequency changes in the same (opposite) direction as the parameter value. Green (red) cells represent earlier (later) investment timing when increasing the respective parameter values.

Table 4.1: The impact of altering parameter values on the operator's decision. The arrows represent frequency changes in the same direction (upward pointing) and opposite direction (downward pointing) of changes in the respective parameter values. The colors represent earlier investment (green) and later investment (red) when increasing respective parameter values. White cells indicate that changes can be considered negligible.

Parameter	Description	Impact on OWF	Impact on PFS	Impact on Never
CT_{OWF}	Construction time of the OWF	↘		↗
CT_{PFS}	Construction time of the PFS solution		↘	↗
d	Enova subsidy given to the OWF	↗	↘	↘
Δ_{NOx}	Annual increase of the NOx tax			
f_{OWF}	Platform energy demand covered by the OWF	↗		↘
I_{OWF}	PV of costs related to the OWF in year 1	↘	↗	↗
I_{PFS}	PFS investment cost	↗	↘	↗
l	Reduction in LCOE of floating OWFs until 2030	↗		↘
L_{OWF}	Lifetime of the OWF			
L_P	Remaining platform lifetime	↗	↗	↘
η_{GT}	Gas turbine efficiency		↘	↗
$\overline{P}_{el}$	Electricity price ceiling	↗	↘	
$\overline{P}_{EUA}$	EUA price ceiling	↗	↗	↘
$\overline{P}_{gas}$	Internal gas price ceiling			
ρ	The operator's discount rate		↘	↗
s_2	Scaling constant for GHG emissions		↗	↘
s_3	Scaling constant for CA			
σ_{EL}	Volatility of electricity price	↗	↘	↘
σ_{EUA}	Volatility of EUA price	↘	↘	↗
σ_{NG}	Volatility of internal gas price	↘	↘	↗
T	Final year of Enova subsidies to floating OWFs	↗		↘
w_1	Weight assigned to the NPV-objective		↘	↗
w_2	Weight assigned to the GHG-objective	↘	↗	↘
w_3	Weight assigned to the CA-objective	↗	↘	↘

From Table 4.1, we see that increasing the volatility of the electricity price or internal gas price leads to earlier investment in PFS. A standard insight from ROs theory is that increasing volatility implies greater uncertainty and delays investment. Therefore, it is interesting to note that this is not always the case in this problem. This is due to the fact that the lifetime of PFS is at least as long as the remaining platform lifetime. Hence, earlier investment allows the operator to reduce the forgone revenues from burning gas instead of selling it. Additionally, the expected future internal gas price increases with volatility, further raising the benefit of early investment as larger losses are incurred by delaying. Increasing the electricity price volatility leads to earlier investment as the in-the-money paths yield higher expected value. The out-of-the-money paths have worse expected value but do not impact the investment timing as an investment is never made in these paths.

Another interesting insight from Table 4.1 is that increasing the volatility of the EUA price or internal gas price leads the operator to refrain from investing in electrification alternatives more often. This may seem counter-intuitive as the increasing price volatility leads to a higher expected value of the electrification alternatives. However, the increasing volatility also leads to a higher continuation value that incentivizes the operator to wait for more extreme price scenarios. If these extreme prices fail to materialize, the operator ends up never investing.

For platforms with long remaining lifetime, we find that electrification alternatives should be pursued as the expected objective value obtained is so high that forgoing investment is only occasionally optimal. Shortening the lifetime increases the frequency of never investing, as can be seen from Table 4.1. In Figure 4.5, the frequency of the optimal strategy is plotted as a function of the remaining platform lifetime. Here, optimal strategy refers to the percentage of paths where each alternative is chosen, according to the LSM decision rule. Consequently, the colored lines represent each alternative. This is the case for all the following figures in this chapter. For lifetimes above 15 years, it is optimal to pursue PFS, while for a platform with a shorter remaining lifetime continuing to burn natural gas is optimal. However, PFS may still be a viable alternative for operators of platforms with short remaining lifetimes as it may allow for lifetime extension in cases where limited gas reserves inhibit gas turbine power production. An example is the Norwegian O&G operator OKEA ASA, who currently considers a PFS solution for the Draugen field (OKEA ASA, 2021).

Our findings in Figure 4.5 provides an additional noteworthy insight: The OWF is never the preferred alternative for the operator, regardless of the remaining platform lifetime. This suggests that, under current conditions, it is unlikely that investments in small-scale off-grid floating OWFs are considered economically viable by companies on the NCS to power their O&G platforms. This would delay the development of the Norwegian offshore wind industry and curtail the potential of decarbonizing O&G operations as a learning step to reduce costs, gain experience, and kick-start the industry, a stated goal by the Norwegian government. Therefore, further action by the government is recommended to stimulate corporate investment in small-scale off-grid floating OWFs and to support the desired growth of the Norwegian offshore wind industry.

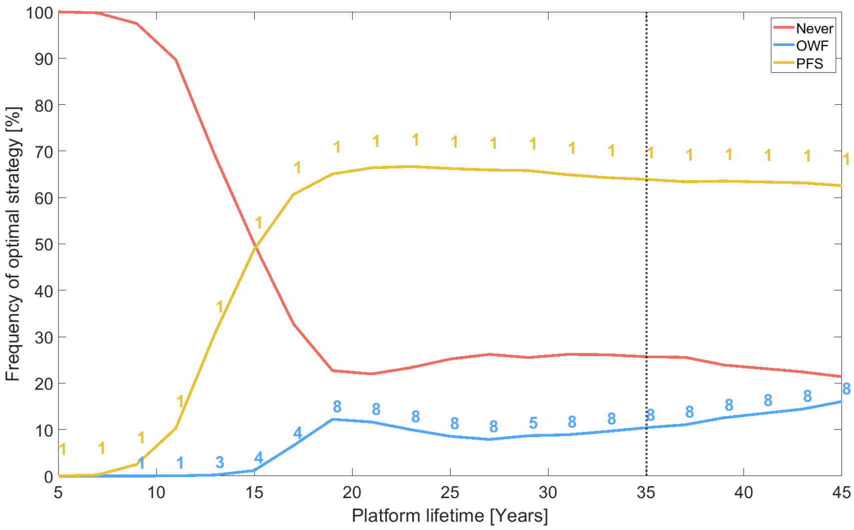


Figure 4.5: The frequency of the optimal strategy as a function of the remaining platform lifetime. The dotted line indicates the base-case value. The numbers represent the most frequent investment timing. 100,000 paths are generated per lifetime increment.

4.3 What does it take to make the offshore wind farm optimal?

In this section, we explore different conditions in the search for scenarios where the OWF is the optimal solution to the operator's decision problem. For the base-case parameter set, the OWF is the optimal choice in only 10.0% of the paths. In these paths, the electricity price is often high, making PFS too expensive. High future CC taxes tend to make PFS optimal as it eliminates all emissions, while the OWF only allows emission reductions of 35%. In order to determine which CC tax levels make the OWF competitive while we maintain the stochastic nature of the EUA price, we analyze the impact of reducing the ceiling[16] of the EUA price from 50 NOK/kg CO_2. Figure 4.6 presents the frequency of the optimal strategy as a function of the CC tax ceiling. As can be observed, PFS dominates for ceilings above the 2030 government target of 2 NOK/kg CO_2, while the OWF is never optimal. Hence, the planned taxation strategy seems to agree with the goal of cutting emissions on the NCS but is discouraging to the ambition of developing a national offshore wind industry. In order to better study which alternative is optimal for lower tax levels, we plot Figure 4.7. The figure shows the same results as Figure 4.6 but focuses exclusively on CC tax ceilings between 0 and 2 NOK/kg CO_2. When the ceiling goes below the 2030 target, the floor imposed by the government is set equal to the CC tax ceiling. This adjustment corresponds to a downward shift of the solid blue line presented in Figure 3.2. As can be observed from Figure 4.6, PFS is the optimal alternative for CC taxes above 1 NOK/kg, while never investing is preferred for lower tax levels. The OWF is never the preferred alternative under any tax ceiling but is most competitive around the current tax level of 0.98 NOK/kg CO_2. To conclude, reducing the CC tax ceiling is not sufficient to make the OWF optimal.

[16]As we wish to account for the uncertainty of the EUA price, we reduce the price ceiling instead of assigning a constant deterministic value to the price.

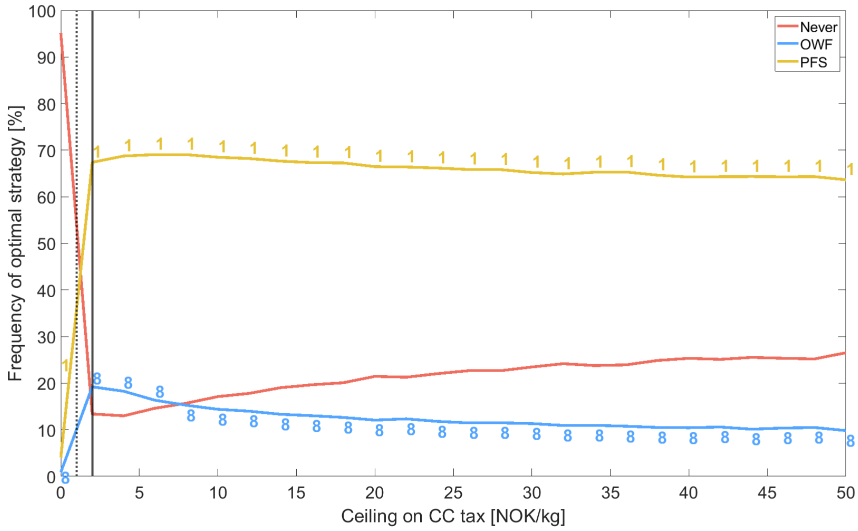


Figure 4.6: The frequency of the optimal strategy as a function of the CC tax ceiling. The solid line indicates the 2030 target set by the Norwegian government. The dotted line indicates the current CC tax level. The numbers represent the optimal investment timing. 100,000 paths are generated per tax increment.

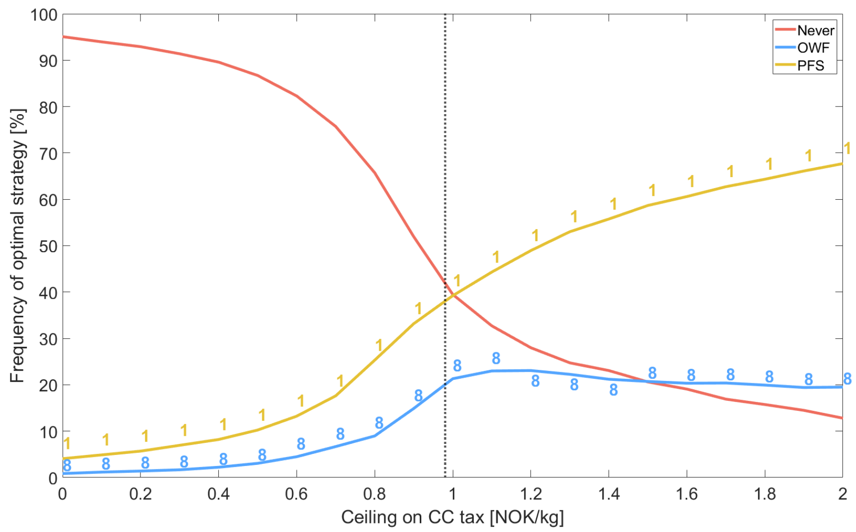


Figure 4.7: The frequency of the optimal strategy as a function of the CC tax ceiling. The dotted line indicates the current CC tax level. The numbers represent the optimal investment timing. 100,000 paths are generated per tax increment.

As mentioned above, the OWF is at its most competitive in low-tax scenarios. Therefore, to further investigate what it would take to make the OWF optimal, we alter other parameter values while keeping CC taxes between 0 and 2 NOK/kg CO_2. First, in Figure 4.8, we consider the extreme scenario where floating OWF costs are fully subsidized. Fully subsidizing the costs makes the OWF the best alternative for the operator, provided that CC taxes do not exceed 2 NOK/kg CO_2. If taxes remain at their current level throughout the platform's lifetime, the OWF is selected in almost all paths. As taxes increase, the OWF becomes less competitive and finally surpassed by PFS at the 2030 government tax target. Hence, our results suggest that if the Norwegian government enacts the planned price floor on CC taxes, even a fully subsidized off-grid OWF will be inferior to PFS. These insights suggest that the carbon taxation strategy conflicts with the ambition of developing a national offshore wind industry.

The results presented in Figure 4.8 provide another interesting observation. Fully subsidizing floating OWFs incentivizes earlier investment. Increasing the subsidy from 40% to 100% changes the optimal investment timing of the OWF from year 8 to year 1. This change is due to the operator choosing to collect the largest possible value from CA when there is no benefit from discounting the investment cost. Hence, fully subsidizing floating OWFs would yield a desired corporate response for the government, as it accelerates national offshore wind industry development. This insight suggests that policy-makers face a trade-off between facilitating industry growth and increasing public expenditure.

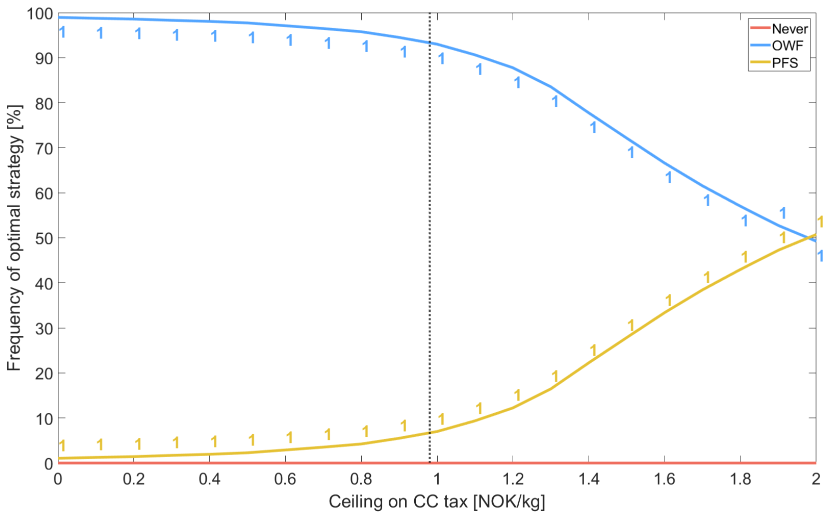


Figure 4.8: The frequency of the optimal strategy when the OWF is fully subsidized. The frequency is plotted as a function of the CC tax ceiling. The dotted line indicates the current CC tax level. The numbers represent the optimal investment timing. 100,000 paths are generated per tax increment.

We now consider scenarios where subsidies are set to 60% and 80% of the OWF's CAPEX. The results for these cases are presented in Figure 4.9. The figure illustrates how higher subsidy levels benefit OWF investments. The range of CC tax ceilings where the OWF is optimal is shifted from 0.65 to 1.15 NOK/kg CO_2 for 60% support (solid lines) to 0.3 to 1.4 NOK/kg CO_2 for 80% support (dashed lines). In both scenarios, the OWF is optimal around the current tax level, while PFS dominates for taxes approaching the 2030 target. Hence, we see that increased subsidies make the OWF optimal for sufficiently low future taxes.

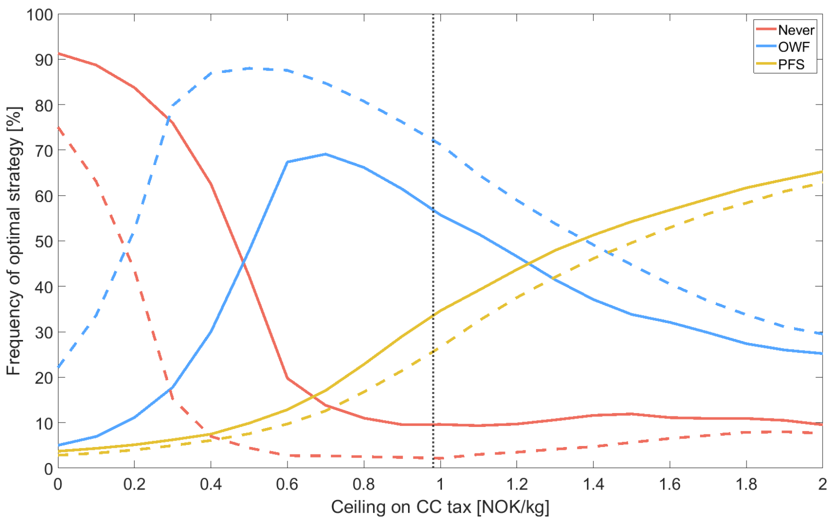
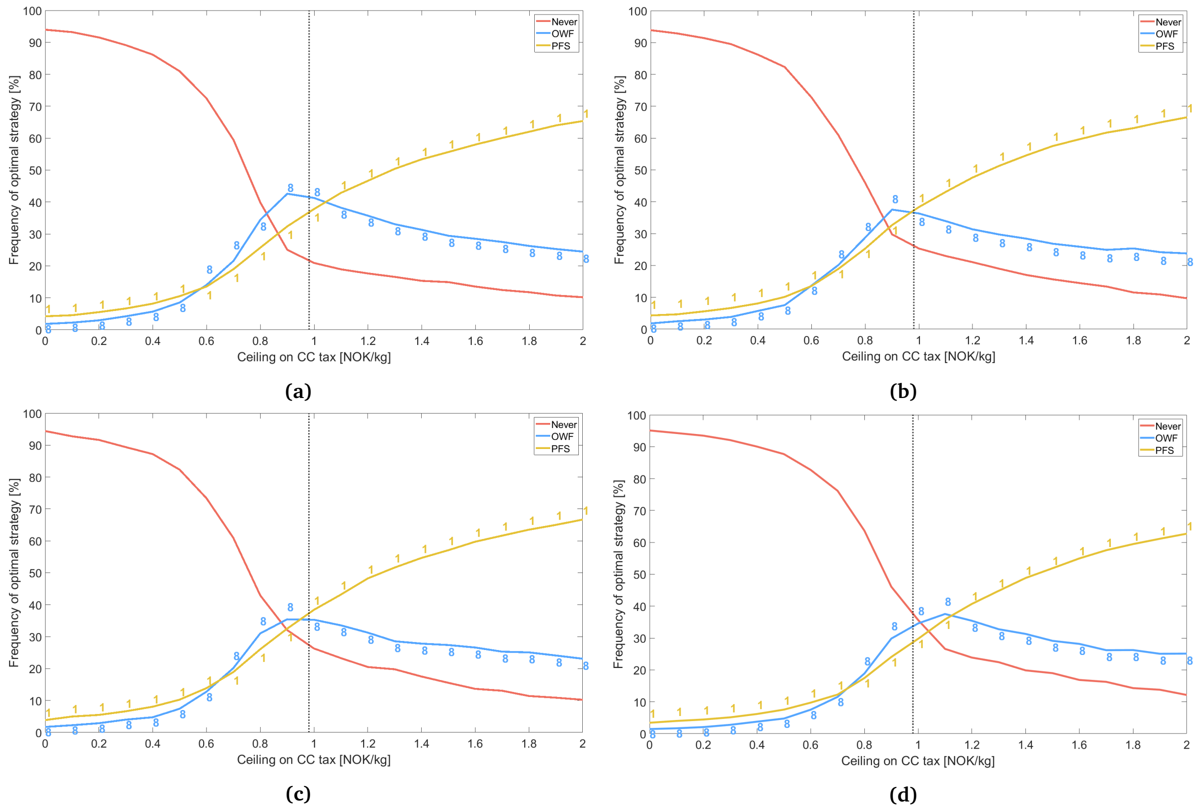


Figure 4.9: The frequency of the optimal strategy with Enova subsidy covering 60% (solid lines) and 80% (dashed lines), respectively, of the OWF's CAPEX. The frequency is plotted as a function of the CC tax ceiling. The dotted vertical line indicates the current CC tax level. The optimal timing is year 1 for PFS and year 8 for the OWF for all increments. 100,000 paths are generated per tax increment.

In order to discover other conditions that make the OWF optimal for low taxes, an extensive sensitivity analysis is performed. We find that numerous circumstances lead the OWF to become optimal if taxes remain around the current level for the entirety of the platform's lifetime. Figure 4.10 presents a selection of this analysis. The figure shows the frequency of the optimal strategy for: (a) partial supply of 40%[17] from the OWF, (b) an OWF lifetime of 30 years, (c) a reduction in LCOE of 15% every third year until 2030 for floating OWFs, and (d) a gas turbine efficiency of 35%. We consider the above scenarios feasible, but they are dependent on future technological innovations, platform characteristics, or maintenance strategies of OWFs. Scenario (a) assumes future technology innovation that allows offshore wind to mitigate intermittency issues reliably. This could be achieved through the use of batteries or hydrogen as energy carriers. As this is highly speculative, we only consider a conservative increase to 40%. Scenario (b) assumes that technical innovations and maintenance improvements allow wind turbines to operate for 30 years. We consider this realistic, as the Norwegian government presumes that OWFs may be operative for up to 30 years on the NCS (Erdal and Reinfjord, 2020). Scenario (c) represents Equinor's best-case projection for cost reductions related to offshore wind supply chain and technology development. Scenario (d) assumes improved efficiency of the gas turbines utilized on the platform. As certain platforms on the NCS have gas turbines with efficiencies approaching 40%, we consider this a likely situation (Norwegian Petroleum Directorate et al., 2008; Vandenbussche et al., 2021). To summarize, only if taxes remain around their current value of 0.98 NOK/kg CO_2, an off-grid floating OWF presents the optimal alternative for optimistic scenarios related to technology improvement, cost reductions, or subsidy increase. Accordingly, our results strongly suggest that if the Norwegian government adopts the CC tax floor at 2 NOK/kg CO_2, small-scale off-grid floating OWFs will fail to materialize. This would slow down cost reductions and the acquisition of valuable experience related to floating offshore wind. Thus, reducing the probability of the government achieving its ambitions for the Norwegian floating offshore wind industry.



(a) (b)

(c) (d)

Figure 4.10: The frequency of the optimal strategy as a function of the CC tax ceiling. The dotted lines indicates the current CC tax level. The numbers represent the most frequent investment timing. 100,000 paths are generated per tax increment. The optimal strategies are plotted for (a) 40% partial electrification from the OWF, (b) an OWF lifetime of 30 years, (c) a reduction in LCOE of floating OWFs at 15% every third year, and (d) a gas turbine efficiency of 35%.

[17]Increasing power supply leads to a larger power rating of the OWF. At 40%, this corresponds to 34 MW. We have assumed that the price of an off-grid floating OWF of this size is equivalent to the base-case price, which is for 30 MW.

We have previously looked at scenarios with low CC taxes coupled with increased subsidies, cost reductions, or technological improvement. We found that small-scale off-grid floating OWFs are only competitive when taxes remain around the current level and additional optimistic conditions occur. To investigate other circumstances that could make such OWFs optimal, we now consider a scenario where the investment cost of PFS is increased. For the base case, we assumed minimal modification costs required for the platform to accommodate PFS. However, numerous platforms on the NCS operate 60 Hz electricity systems. As the Norwegian grid has a frequency of 50 Hz, such platforms require frequency conversion to use PFS. This entails modifications and a greater PFS investment cost than our base-case estimate of 2,500 million NOK. Additionally, required modifications related to platform size and weight constraints may lead to further cost increase (Norwegian Petroleum Directorate et al., 2020). In Figure 4.11, we illustrate how the frequency of the optimal strategy and most prevalent timing changes for increasing levels of PFS investment cost. The dotted vertical lines represent the expected PFS investment cost for the base-case platform located at different distances from shore. The green line corresponds to a distance from shore of 53 km, equivalent to that of the platform nearest shore. The black line corresponds to the base-case distance of 207 km. The purple line corresponds to a distance from shore of 330 km, equivalent to that of the platform furthest from shore in the Southern North Sea cluster. The results indicate that PFS becomes less competitive with higher investment cost but remains optimal as long as the cost stays below 4,400 million NOK. The OWF is increasingly competitive with higher PFS investment cost and becomes optimal for costs surpassing 4,800 million NOK. The impact of the PFS investment cost on the alternative of never investing is ambiguous. The frequency of never investing increases until it becomes the optimal alternative at 4,400 million NOK and then decreases slightly. We attribute this to the fact that it generally increases with higher PFS investment cost, but as this value becomes sufficiently large, the continuation value of PFS becomes low. This, in turn, leads the operator rather to choose to invest in the OWF than waiting for more favorable conditions for PFS. These findings suggest that additional modification costs of 1,900 million NOK compared to the base-case value are required for PFS not to be pursued. For platforms located the furthest away from shore in the Southern North Sea cluster, only supplementary modification costs of 800 million NOK would be necessary. Such modification costs are not unrealistic as multiple platforms in this cluster operate at 60 Hz. The optimal investment strategy for operators in this cluster under low tax ceilings is shown in Figure 4.12. The results indicate that the OWF is the preferred alternative for CC taxes in the range of 0.9 to 1.8 NOK/kg CO_2. We see that at the planned 2030 tax floor of 2 NOK/kg CO_2, PFS is the optimal alternative. This corresponds with our previous findings and again suggests that the Norwegian tax strategy is a limiting factor to small-scale off-grid floating OWF developments. However, for platforms where additional modification costs are required, the OWF is be the optimal decision if the operator's platform is located in the Southern North Sea and taxes remain lower or equal to the planned floor throughout the platform's lifetime. As previously mentioned, some platforms on the NCS are likely to require such costs. Therefore, an off-grid floating OWF is likely to be optimal for certain operators under favorable tax regimes. At the same time, with stated policies, the OWF is only optimal for our operator in the Norwegian Sea if the platform requires supplementary modification costs of at least 2,300 million NOK, an increase of 92% compared to our base-case value.

The results from our previous analyses indicate that small-scale off-grid floating OWFs may become optimal for operators on the NCS through changes in exogenous parameters, such as the CC tax and PFS investment cost. To evaluate whether the operator's relative preference of objectives impacts the optimal decision, we perform a sensitivity analysis of weights. Figure 4.13 presents the optimal strategy as a function of the assigned weights. In the figures, the weights that are not depicted are kept equivalent and equal to $\frac{1-w}{2}$, where w is the weight of the plotted objective at the respective increments. Our results indicate that immediate investment in PFS is an optimal decision that is highly robust to changes in weights. Furthermore, the OWF is only optimal if the operator has a strong preference for the CA-objective, while continuing to burn natural gas is never optimal. Likewise, changing the operator's belief of appropriate scaling constants yields similar results. Increasing the scaling constant of GHG emissions yields a graph similar to Figure 4.13a, while increasing the scaling constant of CA yields a graph similar to Figure 4.13b. Interestingly, for large weights assigned to GHG emissions or small weights assigned to NPV, the optimal timing for investments in the OWF is significantly delayed. This is due to the fact that the relative importance of GHG emissions is high for these weights. As PFS eliminates all emissions, its continuation value is high, and the operator then prefers this alternative. When very high electricity prices lead to insufficient PFS exercise value, he waits for the price to decline. If this decline has not yet occurred near the end of the platform's lifetime, he is forced to invest in the OWF to achieve any emission reduction at all. An additional insight from our results is that for the operator to be willing to pursue electrification with the OWF, he must value CA enough to forgo short-term profitability and emission reductions. This, coupled with the fact that at the decision timing, the Norwegian government had not yet stated that a floor on CC taxes would be imposed, may be the reason behind Equinor deciding to invest in Hywind Tampen, despite our results suggesting that PFS generally is a superior alternative.

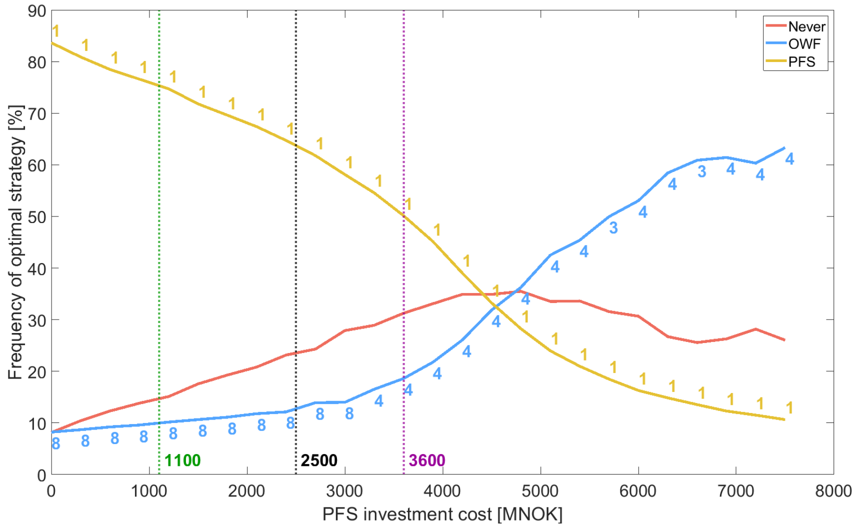


Figure 4.11: The frequency of the optimal strategy as a function of the PFS investment cost. The dotted vertical lines represent the expected PFS investment cost for the platform on the NCS nearest from shore (green), base case (black) and Southern North Sea (purple) from shore (ABB, 2021). The numbers represent the optimal investment timing. 100,000 paths are generated per cost increment.

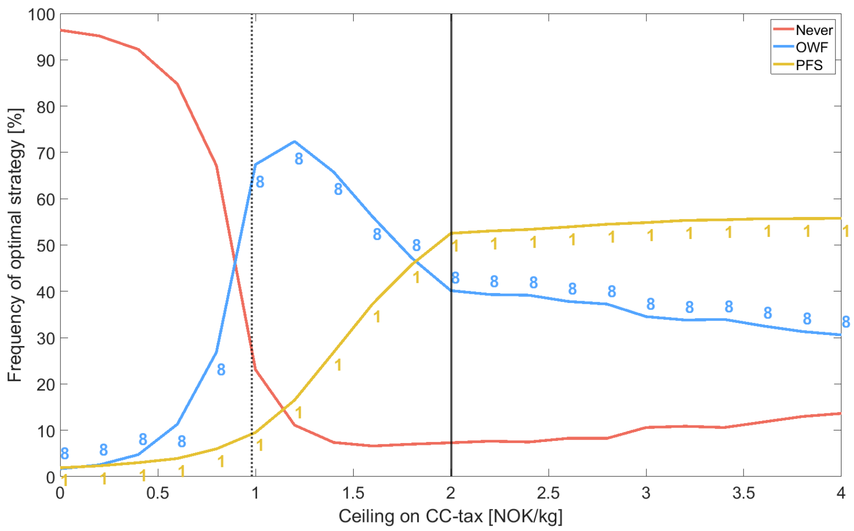


Figure 4.12: The frequency of the optimal strategy as a function of the CC tax ceiling. The PFS investment cost is set to 3,600 million NOK. The solid line indicates the 2030 target set by the Norwegian government. The dotted line indicates the current CC tax level. The numbers represent the optimal investment timing. 100,000 paths are generated per tax increment.

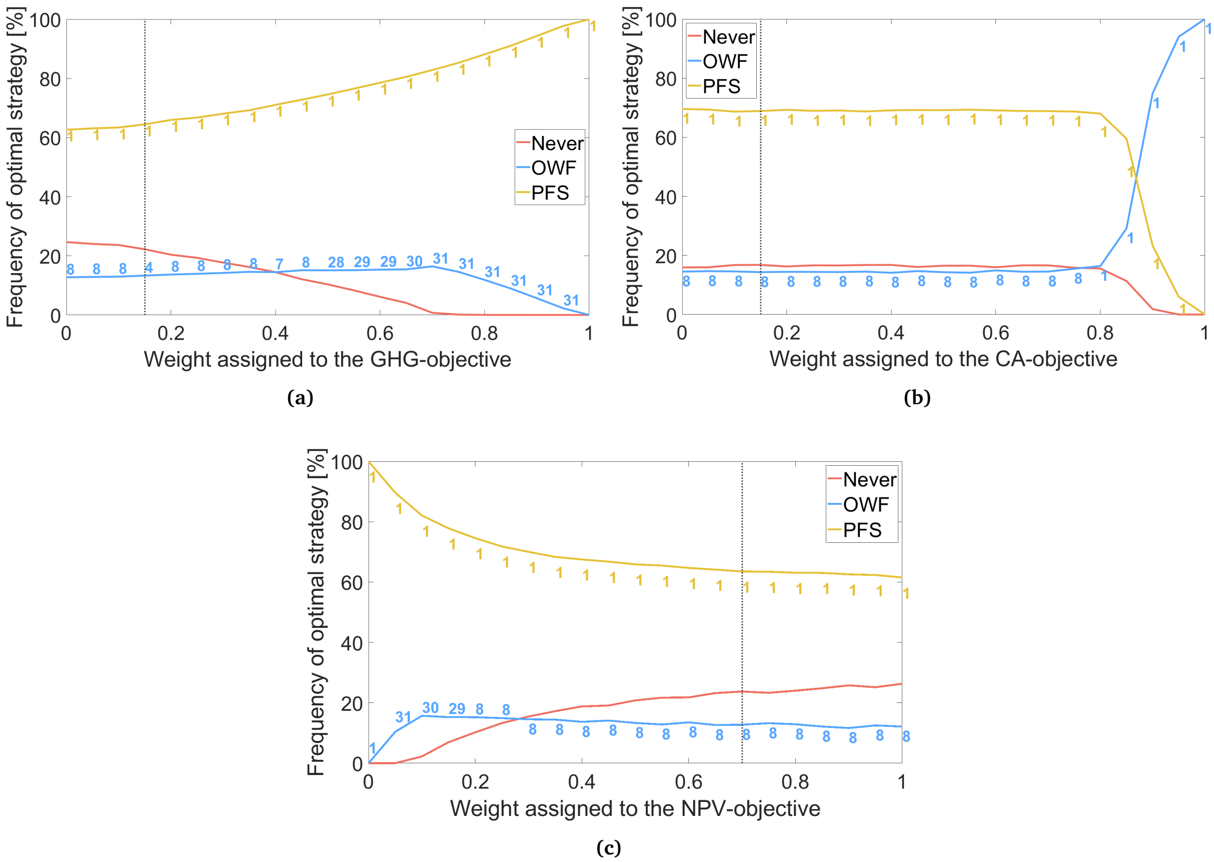


Figure 4.13: The impact on the frequency of the optimal strategy when changing the weight assigned to (a) the GHG-objective, (b) the CA-objective, and (c) the NPV-objective. The objectives not shown are kept equivalent and equal to $\frac{1-w}{2}$, where w is the weight of the plotted objective at the given increment. The dotted line indicates the base-case value. 100,000 paths are generated per increment.

Our results strongly indicate that off-grid offshore wind faces a somber future on the NCS if the government follows through on its announced carbon tax strategy. One might then ask, "Why do numerous companies currently claim to have ambitions to develop OWFs on the NCS?". We believe that there are mainly three reasons behind this. Firstly, several of the planned projects will utilize fixed-bottom turbines. This technology is more mature with significantly lower costs than floating. This applies to the projects targeting Sørlige Nordsjø II, adjacent to the Southern North Sea cluster where the water depth of the NCS is at its lowest (65-72 m) (Torbjørnsdal, 2020; Arendals Fossekompani, 2021; Equinor, 2021b; Norseman Wind AS, 2021; Statkraft, 2021). Secondly, the rated power of the projects envisioned is typically at least an order of magnitude larger than that of the OWF considered in this paper. For projects of such sizes, we can assume that economies of scale decrease the LCOE to a larger extent. Finally, due to large project sizes, the planned OWFs must be connected to the grid as the combined power demand of O&G platforms within feasible proximity of the wind farms is insufficient. This results in full electrification of connected platforms and surplus power sold on the national grid. This means that there are significant differences between the small-scale off-grid floating OWF studied in this paper and the recently announced projects on the NCS. Nevertheless, due to the vast areas where floating technology is applicable and the success of recent pilot projects, many international developers are starting to research and develop the technology to position themselves in the market strategically (Repsol, 2020; Eni, 2021; Iberdrola, 2021; Lee, 2021; Shell, 2021). Hence, to obtain first-mover advantages and become global technology leaders, it is urgent for Norwegian companies to develop small-scale floating OWFs.

Chapter 5

Conclusion

This paper studies the economic attractiveness of small-scale off-grid floating offshore wind farms (OWF) as an electrification alternative to corporate operators of oil and gas platforms on the Norwegian continental shelf. The model employed expands on existing literature by applying real options valuation, implemented through the least squares Monte Carlo method, to a multi-objective decision problem. We illustrate how several objectives can be incorporated into a real options-based decision framework by considering an operator that, in addition to maximizing the net present value of operations, wants to reduce greenhouse gas emissions and obtain a competitive advantage in the floating offshore wind industry. In order to make the objectives comparable, scaling constants are assigned to the non-monetary objectives. Along with weights, these represent the operator's preferences and beliefs. Extending real options valuation to multi-objective problems significantly broadens its application area as complex real-world problems often entail multiple objectives.

We find that the CO_2-tax is one of the most important factors in deciding whether small-scale off-grid floating OWFs are economically attractive. For current tax levels, such OWFs represent a competitive alternative. However, the Norwegian government plans to enact a price floor on CO_2-taxes from 2030 on. The floor is set to more than twice the current level, and if enacted, we find the corporate response to be investing immediately in power from shore (PFS) to electrify platforms. This response is further amplified by the expected increase in EU allowances price. This is in line with the government's goal of reducing emissions on the Norwegian continental shelf but is detrimental to the ambition of rapidly developing a national offshore wind industry and realizing first-mover advantages on the global scale. As long as the tax target is imposed at 2 NOK/kg CO_2, off-grid OWFs remain an inferior alternative to PFS, even with significant subsidies and technological improvements.

Our sensitivity analysis suggests that immediate investment in PFS is an optimal decision that is robust to the operator's relative preference of objectives. Small-scale off-grid floating OWFs are only optimal for operators willing to sacrifice short-term profits to obtain competitive advantage in the floating offshore wind industry. We find immediate investment in PFS optimal for operators of platforms with a remaining lifetime exceeding 15 years. For shorter lifetimes, it is optimal to continue using on-site gas turbines to provide the power required by the platform. Hence, for platforms with sufficient remaining lifetimes, electrification alternatives are desirable for the operator. Furthermore, our results indicate that small-scale off-grid floating OWFs become the optimal alternative for platforms entailing sufficiently high PFS investment cost. This only applies to platforms that require significant adjustments due to weight and size constraints or modification of the electrical infrastructure. Our analysis and results further emphasize that policy action is vital to trigger corporate investment in small-scale off-grid floating OWFs and support the desired growth of the Norwegian offshore wind industry. In conclusion, our results indicate that for off-grid floating OWFs to be optimal for operators on the Norwegian continental shelf, future carbon taxes must remain around current levels, their platforms must require substantial PFS investment costs, or they need to have a dominant preference for the objective of maximizing competitive advantage in the floating offshore wind industry.

Expected future CO_2-taxes lead the operator to choose PFS in most scenarios as this choice completely eliminates emissions, while an off-grid OWF only partially reduces emissions. A grid-connected OWF overcomes this competitive edge, as it is not limited by intermittency issues and may fully electrify the platform. Additionally, it allows for a larger project size resulting in economies of scale. With numerous companies expressing interest in developing large-scale OWFs connected to the Norwegian grid, our results indicate that future research should consider this as an electrification alternative. Furthermore, our findings reveal insights regarding the corporate response to different actions taken by policy-makers, such as increasing taxes and subsidies. As these actions substantially impact corporate decisions, future studies should extend our model by incorporating a public policy perspective.

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Appendix A

Individual scatter plots of optimal base-case solutions

In Figure 4.3, some of the optimal solutions are concealed by other solutions. To show all optimal base-case solutions as a function of mean electricity price and CC tax over the platform's lifetime, individual scatter plots for each alternative are presented in this appendix. Figure A.1 indicates all paths where PFS is optimal, Figure A.2 indicates all paths where the OWF is optimal, and Figure A.3 indicates all paths where it is optimal to never invest.

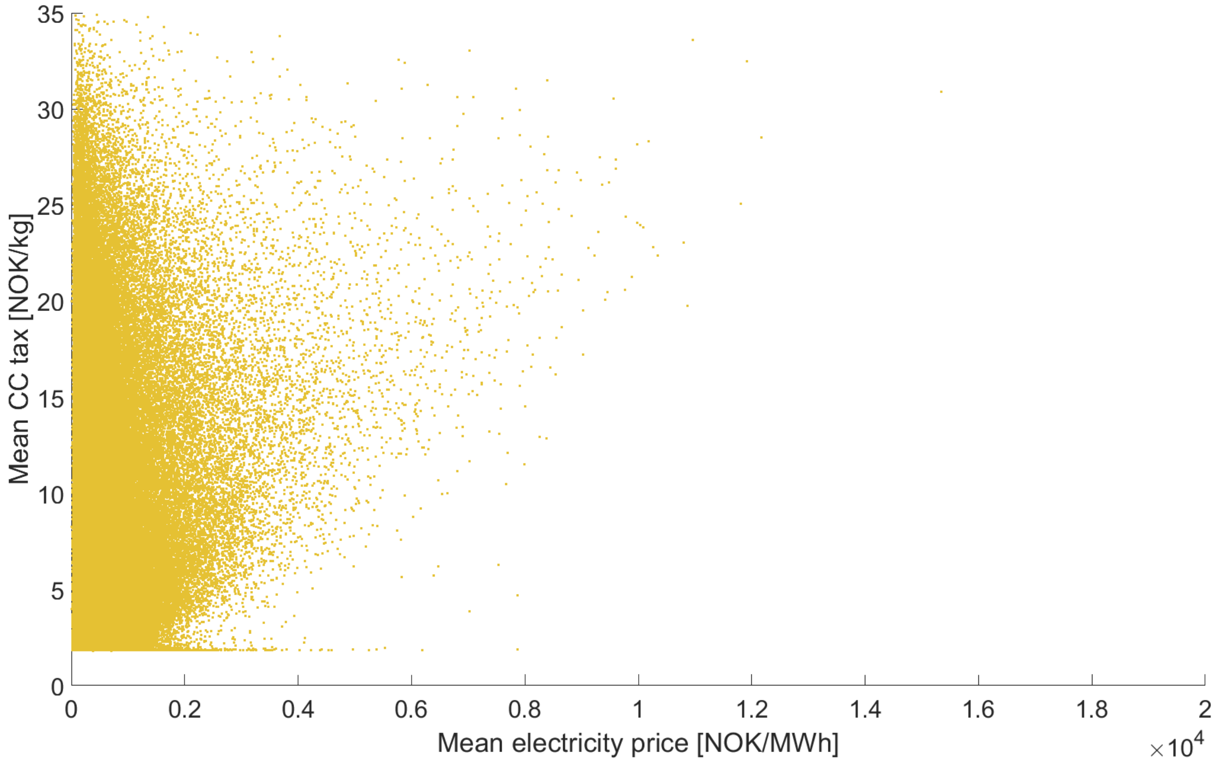

Figure A.1: Scatter plot showing base-case paths where the operator invests in PFS when following the LSM decision rule as a function of mean electricity price and CC tax over the platform's remaining lifetime.

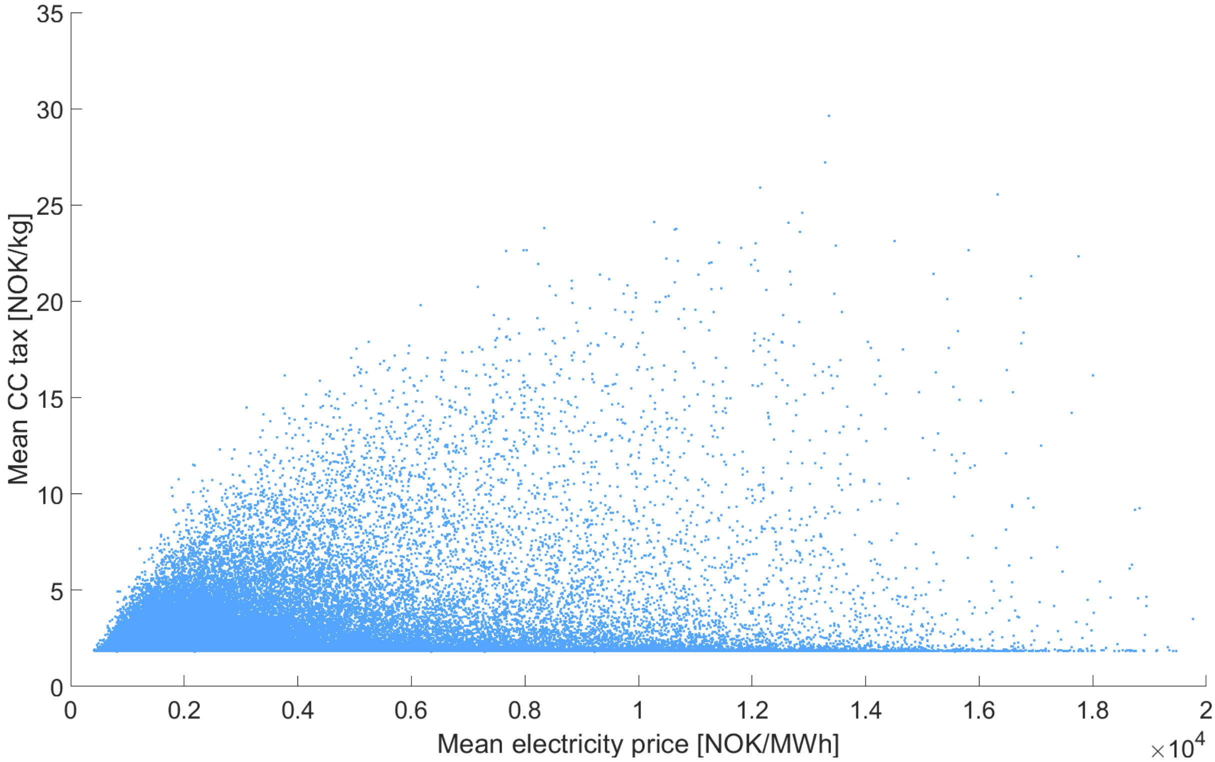

Figure A.2: Scatter plot showing base-case paths where the operator invests in the OWF when following the LSM decision rule as a function of mean electricity price and CC tax over the platform's remaining lifetime.

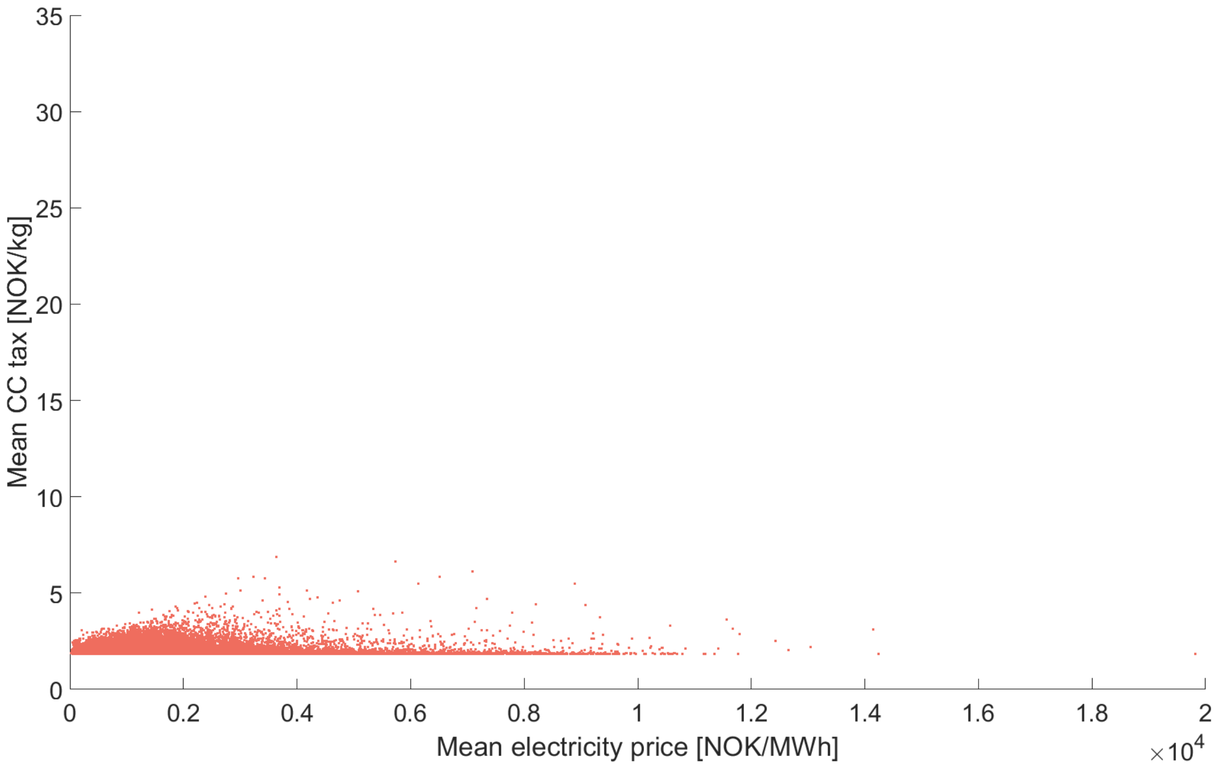

Figure A.3: Scatter plot showing base-case paths where the operator never invests when following the LSM decision rule as a function of mean electricity price and CC tax over the platform's remaining lifetime.