UiA University of Agder

Master

Energy System Modeling for the Integration of Offshore Wind and Onshore Power in Decarbonizing the Oil and Gas Industry

-An analysis of potential electrification pathway scenarios towards 2050

EMILIE ALSAKER MATHIESEN

SUPERVISORS

Kristina Haaskjold and Sathyajith Matthew

University of Agder, 2023

Faculty of Engineering and Science
Department of Engineering Sciences

Individual Declaration

The individual student or group of students is responsible for the use of legal tools, guidelines for their use and rules on the use of sources. The declaration is intended to make the students aware of their responsibility and the consequences of cheating. Missing statement does not release student(s) from their responsibility.

1.	I hereby declare that my thesis is my own work and that I have not used other sources or have received any help other than that mentioned in the thesis.	Yes
2.	**I further declare that this thesis:** • Not have been used for another exam at another deparment/university/college in Norway or abroad. • Does not refer to others work without being stated. • Does not refer to own previous work without being stated. • Include all references used in the bibliography list. • Is not a copy, duplicate or copy of others work or answers.	Yes
3.	I am aware that violation of the above is to be regarded as cheating and may result in annulment of examinations and exclusion from universities and colleges in Norway, see Universitets- og høgskoleloven §§4-7 og 4-8 og Forskrift om eksamen §§ 31.	Yes
4.	I am aware that all submitted assignments can be plagiarism checked.	Yes
5.	I am aware that the University of Agder will consider all cases where there is suspicion of cheating in accordance with the university college's guidelines for handling cases of cheating.	Yes
6.	I have been familiarized with the rules and guidelines for the use of sources and references on the library's website.	Yes

Publishing Agreement

Authorization for electronic publishing of the thesis. The author(s) hold the copyright to the thesis. This means, among other things, the exclusive right to make the work available to the public(Åndsverkloven.§2). Assignments that are exempt from public disclosure or confidential/confidential will not be published.

I hereby give the University of Agder a free right to I hereby grant the University of Agder a free right to make the thesis available for electronic publication:	Yes
Is the thesis confidential?	No
Is the thesis exempt from public disclosure?	No

Abstract

Achieving the green energy transition is a pressing issue to mitigate climate change. This thesis investigates the feasibility and potential of electrifying the Norwegian Continental Shelf (NCS) to reduce emissions to comply with the government's ambitious climate goals towards 2050. An analysis of various scenarios using offshore wind and/or power from shore as electrification alternatives are conducted to determine the most cost-effective solutions, it's impact on the Norwegian energy system, and exploring possibilities of offshore wind in meeting the NCS energy demands. The existing IFE-TIMES-Norway model was updated to implement additional offshore regions and various scenarios were applied to represent the decision problem realistically. To improve the representation of the petroleum industry within TIMES, literature and government electrification plans were incorporated.

The findings highlight the urgency of decarbonizing the NCS and the inadequacy of today's electrification plans for achieving climate targets by 2030. Overall, model simulations indicate that electrifying with power from shore alone or using both offshore wind and shore power results in the most significant reduction in CO_2 emissions. As the most cost-effective solution for decarbonizing the petroleum industry, combining shore power and offshore wind power is emphasized. In spite of this, results indicate that offshore wind is a key factor in limiting the impact of electrification on the energy system and increasing the total production of renewable energy sources. There are limitations related to using only power from shore, such as the availability of grid capacity and whether power from shore projects is prioritized over other industrial projects that also wish to connect to the grid to manage electrification measures to meet targets and government plans. Based on today's offshore wind investment costs and government plans, offshore wind alone cannot provide enough energy to cover O&G demand in 2030. The study's model simulations of different scenarios demonstrated that offshore regions were successfully implemented and provided adequate solutions for electrifying the NCS. The development of offshore wind production sites and the electrification of oil and gas platforms is also proposed.

Sammendrag

Overgangen til det grønne skiftet er avgjørende for å begrense klimaendringene. Denne masteroppgaven undersøker gjennomførbarheten og potensialet for å elektrifisere norsk sokkel for å redusere utslipp og oppfylle regjeringens ambisiøse klimamål frem mot 2050. Det gjennomføres en analyse av ulike scenarier med havvind og/eller kraft fra land som elektrifiseringsalternativer for å finne den mest kostnadseffektive løsningen, påvirkningen på det norske energisystemet, og undersøke mulighetene for om havvind kan dekke energibehovet på norsk sokkel. Den eksisterende IFE-TIMES-Norway modellen ble oppdatert ved å implementere nye offshore regioner, og ulike scenarier ble utarbeidet for å representere beslutningsproblemet realistisk. For å sikre at representasjonen av petroleumsindustrien i TIMES var så realistisk som mulig, ble data fra litteratur og regjeringens elektrifiseringsplaner inkludert i modellen.

Funnene understreker at det haster med å redusere utslippene på norsk sokkel og at deler av elektrifiseringsplanene er for dårlig for å nå dagens klimamål innen 2030. Samlet sett indikerer simuleringene at elektrifisering med kraft fra land alene eller med både havvind og landstrøm gir størst reduksjon i CO_2 utslipp. En kombinasjon mellom havvind og kraft fra land vektlegges som den mest kostnadsseffektive løsningen for å dekarbonisere petroleumsindustrien. Til tross for dette indikerer resultatene at havvind er en nøkkelfaktor for å begrense effekten elektrifisering har på energisystemet ved å øke den totale produksjonen av fornybar energi. Det er begrensninger knyttet til bruk av kun kraft fra land, som tilgjengelighet på nettkapasitet og om kraft fra land prosjekter prioriteres fremfor andre industriprosjekter som også ønsker å knytte seg til nettet for å utføre elektrifiseringstiltak for å oppfylle Norges klimamål. Basert på dagens investeringskostnader for havvind og regjeringens planer, kan ikke havvind alene gi nok energi til å dekke etterspørselen i 2030. Studiets modellsimuleringer av ulike scenarier demonstrerte at offshoreregioner ble implementert med suksess og ga tilstrekkelige løsninger for å elektrifisere norsk sokkel. Modellsimuleringene foreslår hvilke olje og gass installasjoner som bør elektrifiseres i korrelasjon med både utvikling av havvind og kraft fra land.

Acknowledgements

This thesis is submitted as the concluding part of my Master of Science degree in Renewable Energy, at the University of Agder (UiA). The thesis is written as a scientific paper.

I would like to sincerely thank my supervisors, professor Sathyajith Mathew (UiA) and researcher Kristina Haasjold (IFE), for their invaluable guidance, inspiring discussions, and constructive feedback throughout the writing of my master thesis. Their expertise and knowledge have been helpful in successfully completing this thesis. I am also grateful for the opportunity to conduct this research in collaboration with the Institute for Energy Technology (IFE) and for the resources provided by IFE.

Finally, I thank my partner, family, and co-students for their unwavering support during this journey. The completion of this master's thesis marks the end of my academic career for now and the beginning of my career as a professional engineer. I am excited and look forward to the opportunities that lie ahead.

Emilie A.Mat

Emilie Alsaker Mathiesen
University of Agder, Grimstad
May 22, 2023

Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating current
CCS	Carbon capture and storage
DC	Direct current
DE	Denmark
DK	Germany
EA	Environmental Agency
ETSAP	Energy Technology Systems Analysis Program
IEA	International Energy Agency
IFE	Institute for Energy Technology
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NCS	Norwegian Continental Shelf
NL	The Netherlands
NPD	The Norwegian Petroleum Directorate
NVE	The Norwegian Water Resources and Energy Directorate
O&G	Oil and gas
Oemof	The Open Energy Modelling Framework
ONLYPFS	Only power from shore
OW	Offshore wind
PFS	Power from shore
RES	Renewable Energy Sources
RQ	Research questions
SE	Sweden
TIMES	The Integrated MARKAL-EFOM System
UK	The United Kingdom
WWF	World Wildlife Fund

Chapter 1

Introduction

One of the greatest challenges and opportunities of our time is the transition from fossil fuels to renewable energy sources[1]. The Norwegian government has set ambitious climate goals, which include 55% reductions in emissions from 1990 levels by 2030, and reducing to net-zero by 2050. Achieving the Paris Agreement goals is absolutely essential for slowing down climate change and preventing global warming from exceeding 1.5°C. However, the Energy Transition Norway Report 2022 states that *"Norway is not on track to reach its 2030 and 2050 climate targets. There is no evidence that the actions taken are creating the dramatic shift needed to reach these targets. Forecasts show that Norway will have to significantly change its current course to reach the targets in both 2030 and 2050"*[2].

As a result of the Russian invasion of Ukraine, Norway is currently the largest gas supplier to Europe, which has increased pressure on Norway to increase its gas exports[3]. The oil and gas industry, however, was responsible for 33% of Norway's total greenhouse gas emissions in 2021, making it the country's largest emissions sector[2]. Electrification of the shelf is considered necessary to meet climate targets. The electrification of the shelf involves replacing the gas turbines that energize the oil and gas platforms with more sustainable energy sources. Electrification with the use of offshore wind and power from shore are highlighted as the most relevant options based on today's technology. A transition like this requires significant measures to be taken in the power grid, as well as balancing uneven power production, securing power supply, and studying how this impacts the Norwegian power system[4]. Several questions need to be answered at the same time as Europe is at war, there is an energy crisis, inflation is being experienced, and an industry awaits the government's lead. This highlights the importance of putting in place good tools to assess how the power system interacts with different electrification pathways on the Norwegian continental shelf (NCS).

In this regard, the long-term optimization model IFE-TIMES-Norway has been further developed under this study to include a detailed representation of the Norwegian continental shelf, including O&G fields and its interaction with offshore wind and power from shore. The purpose of the study is to explore pathways and impacts of offshore wind and shore power mitigation in decarbonization studies for the oil and gas industry. The report focuses on the integration of new offshore regions into the existing IFE-TIMES-Norway model and its application in a variety of scenarios in order to better understand how electrification scenarios are evaluated under decarbonization constraints and how future electrification impacts the Norwegian energy system on the road to achieving Norway's ambitious climate goals.

1.1 Research Project

This study is a continuing work of the research project conducted by the author of this thesis in autumn 2022 as part of the Master's course *Renewable Energy* at the University of Agder (UiA). The main objective of the pre-study was to look into previous research on electrification of the Norwegian offshore petroleum fields and to develop a methodology to integrate the offshore wind, power from shore, and petroleum regions into IFE-TIMES-Norway[5]. It was suggested that the methodology for integrating offshore wind and O&G regions needs further development to ensure that it makes the most realistic decisions possible and that it incorporates CO_2 emissions from O&G fields. In addition, the article recommended updating the model with more accurate wind data and related capacities and power from shore. As a final note, the article mentions that the expanded functionality of the model will allow it to provide more detailed simulations, further analysis of electrification scenarios, and more options in offshore wind regions. Accordingly, the research project led to the development of this master thesis.

1.2 Report Outline

The paper is organized as follows: After this introductory section, chapter 2 presents a literature review to give a comprehensive overview of electrification and the production activity on the NCS, in addition to the related research on energy system modeling. This is followed by chapter 3 which presents the objectives of the study. Thereafter chapter 4 presents the theoretical background on IFE-TIMES-Norway and relevant theory. Chapter 5 provides the methodical approach used to conduct the implementation and modeling of offshore regions in IFE-TIMES-Norway. The results and discussions are then presented in chapter 6 and critically compared to other studies to answer the research questions. Lastly, chapter 7 concludes with the most important findings and future work recommendations.

Chapter 2

Literature Review

This chapter is divided into three sub-sections. The first one focuses on the recent developments in the electrification of the NCS and highlights the associated challenges. The second reviews the production activity pathways. Further, the third presents literature on the relevant energy system modeling is presented, followed by an overview of previous TIMES model studies.

2.1 Electrification of the NCS

Electrification of the Norwegian continental shelf (NCS) has become a topic of discussion due to the need of reducing CO_2 emissions to comply with climate goals[5]. Several studies have been investigated by industry and government to examine the potential of electrifying the Norwegian Continental Shelf to decrease CO_2 levels. The Norwegian government also envisions developing the offshore wind industry in collaboration with the oil and gas (O&G) industry to reduce emissions while creating future value and job creation[1]. Several studies suggested electrifying the Norwegian continental shelf using offshore wind, hydrogen, power from shore, carbon capture and storage (CCS), and energy efficiency measures. Both references, [4] and [6], emphasized that the feasibility of electrifying a particular installation should be assessed on a case-by-case basis, taking into consideration various factors such as the type of platform, the available space and weight capacity, the expected field lifetime, energy requirements, the proximity to a power source, the level of CO_2 reduction achieved, and the cost involved. The literature highlighted challenges associated with utilizing offshore wind energy, as it leads to inconsistent and uneven energy production[7]. On the other hand, generating power from shore is costly over long distances[4].

A recent article on Power from Shore in [4] was published jointly by the Norwegian Petroleum Directorate, the Norwegian Water Resources and Energy Directorate (NVE), and the Norwegian Environment Agency [5]. The article explored the viability of using power from shore to electrify the various installations on the NCS. It examined the O&G fields that had already adopted or were planning to adopt power from shore and evaluated the expected reductions in CO_2 emissions, associated costs, and challenges in implementing the technology. The article highlighted that emission trading and CO_2 taxes are the primary policy tools used to reduce emissions in the petroleum sector, resulting in a total emission cost of approximately NOK 700 per ton of CO_2[5]. Further, it noted that advancements in technology are making power from shore more affordable and accessible. By 2023, it was projected that 16 fields would use power from shore, which was expected to lead to significant reductions in CO_2 emissions, estimated to be 3.2 million tonnes per year. However, the report also concluded that shore-based power over long distances requires significant investment and that for certain installations, emissions would not be reduced sufficiently to make shore-based power economically viable. Another article in [8] stated that in the event of cancellations or postponements of planned power from shore projects, it would be difficult to reach the climate targets. However, the study in [4] also acknowledged that in certain regions, the implementation of power from shore is not currently feasible due to the lack of grid capacity, which may impact the security of supply. The article warned that the implementation of power from shore plans could lead to an increase in Norwegian electricity prices and a smaller price difference between the north and south.

Report [8] investigated the electricity consumption at the NCS towards 2040 as seen in figure 2.1, forecasted based on potential investment decisions made for power from shore. Additionally, the report considered the company's climate targets, emission forecasts, new fields planned, and decommissioning plans. As seen in the figure, the projected electricity consumption is divided into the following categories; Today/operational, selected/planned, possible/mentioned, and identified/very uncertain. As seen in figure 2.1, the electricity demand on the NCS may range from 7 TWh to 24 TWh in 2040 based on investment decisions in power from shore.

The Norwegian Environmental Agency and Konkraft (composed of Offshore Norway, NI, RF, NHO, LO, United Federation of Trade Unions, and Industry Energy) both provided a comprehensive overview of the efforts and projects aimed at reducing direct emissions in the Norwegian petroleum industry as cited in [9] and [8]. Both reports highlighted several electrification methods, including power from shore, improving efficiency, offshore wind, carbon capture and storage (CCS), hydrogen or ammonia in combustion engines, and high-temperature fuel cells[5]. However, according to [8], the contribution to CO_2 reductions from CCS and power generation from hydrogen or ammonia by 2030 is uncertain due to their current immaturity for offshore purposes. These technologies are therefore expected to become more relevant in the long term. Therefore, among these, power from shore and offshore wind are considered the most promising due to their current use and technology development. However, the report in [9] noted that offshore wind has limited potential for reducing emissions, as it may not be able to fully meet the power demand due to the varying wind conditions. As a result, gas turbine generators and reserve turbines will still be

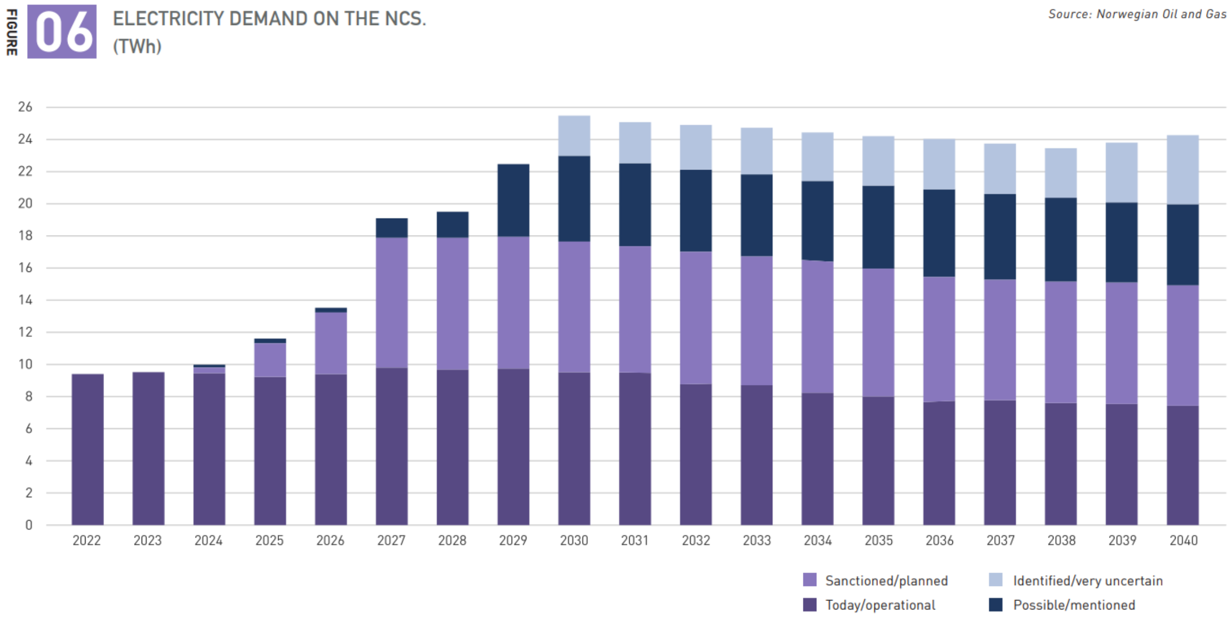


Figure 2.1: Projected electricity demand on the continental shelf for 2021-2040 based on assumptions, government announcements, and decommissioning of fields, not including electrification measures beyond those announced today. Image source: [8].

required. The report also mentioned battery storage as a potential solution to reduce the use of gas turbines. Despite these limitations, [9] estimated that offshore wind could result in a reduction of 150,000 tonnes of CO_2 at the NCS by 2030. The report identified that offshore wind development in Norway faced challenges. The highlighted barriers included limitations on the number of offshore projects that can be undertaken annually by the industry, as well as implementing measures during downtime when a number of other projects also require attention. Fields with a short lifetime are recognized as being less suitable for power from shore or offshore wind, where short-term measures are necessary[5]. Finally, the report proposed linking the wind park to fields that already have power from shore to make the power bidirectional, which would allow offshore wind farms to provide power to shore when production exceeds the platform demand. Other studies, such as those cited in [10], [11], and [12], also explored some of the options for electrifying the offshore petroleum industry.

The electrification of the NCS also presented challenges posed by the fluctuations in wind energy production. Several studies have explored ways to meet this issue through the connection of dispersed wind power production sites. For example, the study in [7] investigated interconnecting five offshore wind power production sites along the NCS to reduce the intermittency of offshore wind power. This was done by quantifying the potential of collective offshore wind power production by using hourly wind speed data collected over a 16-year period. Another study reported in [7], that spreading wind power production across multiple locations could lower fluctuations and decrease the risk of not producing wind energy. Another study in [13] examined the benefits of spreading wind power production over a larger geographical area. This was done by using an optimization method to balance out two key factors: reducing wind power output fluctuations and increasing the overall average output. The results in [13] demonstrated that spreading wind power production over a larger area could improve the average output and reduce low output periods. These findings highlighted the importance of considering the allocation of wind power production sites in the electrification of the NCS.

2.2 Production Activity Pathways on the NCS

There has been considerable debate regarding the production activity on the NCS towards 2050, with numerous sources suggesting different levels of production activity pathways[14][15][16].

Several global organizations have recommended phasing out the oil and gas (O&G) industry as soon as possible according to published reports. World Wildlife Fund (WWF)[16], International Energy Agency (IEA)[15] and European Union (EU)[14] pointed out that the most important cause of climate change is emissions from oil, coal, and gas. Accordingly, the RepowerEU report 2023 in [14], stated that a significant increase in energy generation from renewable sources is essential to replace fossil fuels and reduce emissions. Additionally, IEA[15] stated that no new investments in O&G fields exploitation should be approved beyond those committed by 2021 if the world intends to meet the Paris Agreement. Even though Europe needs additional gas supply due to the Ukrainian invasion, new O&G discoveries in Norway will not solve the precarious and immediate need for gas. WWF[16] highlighted that production start takes on average 16 years from the time of discovery, meaning that any new oil and gas would not be available before approaching 2040. Considering that the EU has committed to being carbon neutral by 2050, the need for Norwegian O&G is highly uncertain[14].

Despite the recommendations mentioned above, politicians continue to announce new concessions and exploration licenses on the NCS. In [17], the Norwegian Petroleum Directorate

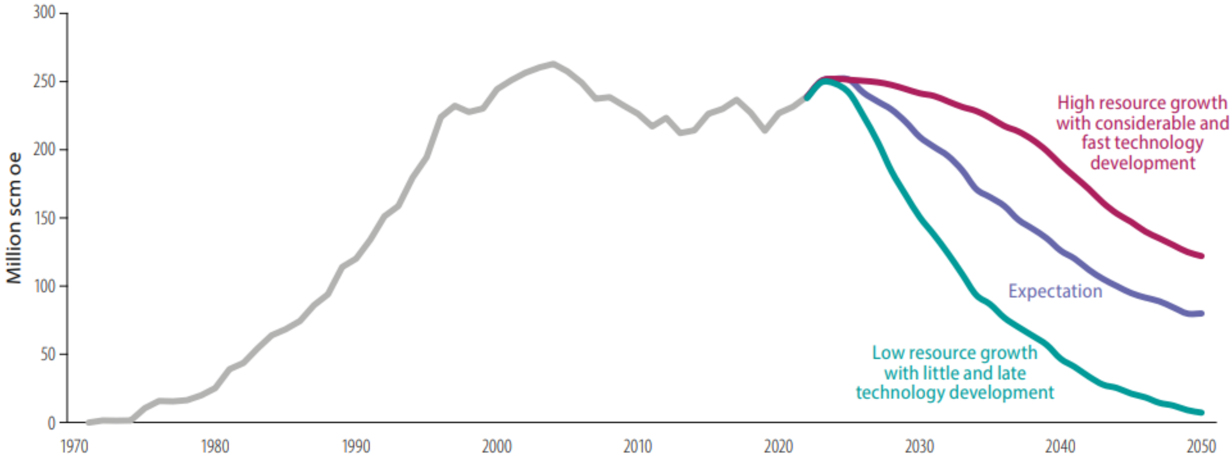


Figure 2.2: Three potential production activity pathways on the Norwegian continental shelf towards 2050, suggested by NPD. Image source:[19]

(NPD) recently announced the grant of 47 new exploration permits to 25 companies on the NCS. A report from the Norwegian government[18] stated that the Norwegian petroleum industry should be developed rather than discontinued. Furthermore, the Petroleum Directorate reported record-high gas production on the NCS in 2022[3]. Based on their estimates, oil production will remain high and increase in the coming years, while gas production will remain at 2022 levels for the next four to five years. Another announcement in [3] presented the high production by the energy crisis in Europe as a result of the ongoing war in Ukraine and a stop in the Russian gas supply. The NPD report in [19] emphasized that there is uncertainty over the future of both production and revenue from the petroleum industry. In order to illustrate the range of potential production activity on the NCS toward 2050, three scenarios are presented by NPD[19] as seen in figure 2.2 above.

Another factor that plays a role in the production activity on the NCS is the lifetime of the various fields. The typical oil production profile throughout its lifetime experiences a rapid increase to a maximum production rate, then a stable period of production, and then a gradual decline[20]. However, the lifetime of an O&G field is often affected by new discoveries, and new investment decisions[20]. The NPD stated that several O&G fields have their lifetime extended by utilizing the capacity of both decommissioned platforms and mature fields with lower production rates than earlier. This allows the existing pipeline infrastructure to have more space for new discoveries to be connected, which in turn increases the overall capacity of the infrastructure. Figure 2.3 illustrates the total historical production and estimated production activity on the NCS towards 2032[20]. The figure is distributed by the maturity of the resources, and divided into the following categories: reserves, resources in discoveries, resources in fields, and undiscovered resources. Based on the policy decisions made regarding the exploration and exploitation of new discoveries, the figure illustrates how production activity can be impacted differently.

The various references demonstrated that there is much uncertainty around the activity levels on the shelf in the time that lies ahead. It is important to note, however, that when considering the activities of the NCS, the government is the authority and, therefore, the most dependable source, but at some point, the government can be influenced by the EU and others.

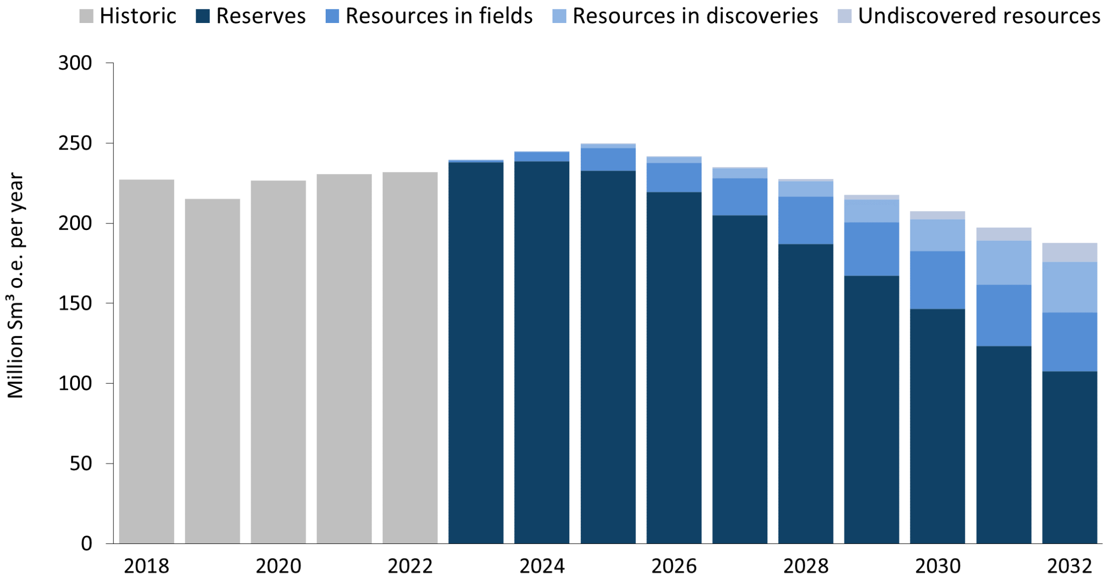


Figure 2.3: Total historical O&G production and production activity forecast towards 2032 on the NCS, divided into categories based on the maturity of the field; reserves, resources in discoveries, resources in fields, and undiscovered resources. Image source:[20].

2.3 Related Research on Energy System Modelling

This section reviews the literature on energy system models, which considers different modeling approaches, compares their features, and examines previous applications of the energy model IFE-TIMES-Norway.

Energy system models have been recognized as a powerful tool for planning future energy systems by understanding the complex interactions between demand and supply, different sources of energy, technologies, and the impact of policy and technological changes on the energy system[21][22]. The models are often utilized by applying different future energy scenarios. Additionally, the models can be used for short-term to long-term energy planning, depending on the modeling approach, for national, local, or multi-regional scales[23]. In energy modeling, the goal is to improve decision-making, and understanding of the energy system dynamics and interactions, or improve system performance. Furthermore, potential outputs from energy system models include energy system costs, energy consumption, energy mix production, energy infrastructure, potential emission reductions, and import and export of electricity.

There are several different approaches to energy system modeling, each with its own strengths and weaknesses. The energy model classification used in [24] distinguishes between top-down and bottom-up approaches. Top-down models use a simplified representation of the energy system and are often used by economists and public administrations. The model is mainly used to evaluate the impacts of energy and climate policies on indicators such as public welfare, employment, and social growth. While bottom-up models provide a detailed analysis from the techno-economic point of view. This study employs a bottom-up approach and is technically based, therefore further review will be conducted in this area.

A widely used bottom-up model is TIMES (The Integrated MARKAL-EFOM System)[25][26]. According to [25], models from this family have rapidly been used to answer research questions within the field of energy planning. Other examples of bottom-up approaches mentioned in literature are MESSAGE (Model for Energy Supply Strategy Alternatives and their

General Environmental Impact)[24][27][28], Oemof (The Open Energy Modelling Framework)[25], and Balmorel[29]. In comparison with MESSAGE and TIMES, Oemof and Balmorel have the main advantage of its accessibility, based on its open-source nature and therefore free to use[24][25][29]. However, Balmorel cannot account for uncertainties, such as political policies, and does not account for all energy sectors, more about the model can be seen in [29]. Table 2.1 shows an overview of the main features of the energy models.

Criteria	TIMES [30]	MESSAGE [27][28]	Oemof [25][24]	Balmorel [29]
Regions	Local, national, regional, global	Global(Adaptable to other regions)	User dependent	Baltic sea
Model type	Optimization, Linear programming	Optimization, Linear programming	Optimization, Linear Programming	Optimization, Linear programming
Built on	GAMS	GAMS	Python	GAMS
Objective	Minimum discounted system cost	Minimizing total costs of energy supply	Costs, emissions	Economic costs
Sectors	All	All	Electricity, heat, mobility	Electricity, district heating
Modelling period	Medium-, long- term	Long-term	Short-, medium-, long- term	Medium-, long- term
Suited for many scenarios	Yes	Yes	No	No

Table 2.1: An overview of various energy models using the bottom-up modeling approach.

As seen in the table, the models have some similar features and are comparable. In spite of this, each model has strengths and weaknesses unique to its use.

Among the energy models presented in table 2.1, the TIMES model is previously used in a number of decarbonization scenario studies. Additionally, [21] highlighted that TIMES can be advantageously used for regional energy system modeling. Furthermore, a number of reports used TIMES (e.g.Ref.[21][31][32][33][34]) to analyze how the energy system interacts with other sectors such as transportation and renewable energy transitions.

The paper in [31] used TIMES to study both the impact of hydrogen transition on the overall economy and the role hydrogen can play in decarbonizing the domestic energy system, the importance of hydrogen as an export product, as well as the drivers and barriers for large-scale hydrogen production in Norway. While, the paper in [21] used TIMES to understand how the Basilicata (Southern-Italy) region could contribute to the achievement of the 2050 national decarbonization targets, where the study aimed to identify possible low-carbon development paths in the region. There is however a lack of literature on the use of TIMES for modeling and evaluating how the petroleum sector can be electrified to reduce CO_2 emissions. This is primarily due to the fact that the current model version is not detailed enough to perform the detailed electrification scenarios of the petroleum industry. Consequently, this master's thesis contributes to the literature relating to decarbonization studies of the petroleum industry and will allow for a greater level of detail in this field.

2.4 Contribution to the Field

The key contributions of this master thesis are twofold. Based on previous studies, it is evident that offshore wind and power from shore are currently the most feasible options for electrifying the NCS. However, few studies have been conducted to examine how electrification develops over time[5] and what would be the resulting impact on the energy system. Previous literature demonstrated a gap in the use of TIMES models to analyze the interplay between offshore wind energy and O&G fields to decarbonize the Norwegian petroleum industry. For this reason, it is considered important to develop a model that can comprehensively optimize the electrification of the NCS and analyze how different electrification pathways can impact the Norwegian energy system, in terms of emission targets, electricity prices, import and export of electricity, and the energy mix. Based on this, the main contribution of this study will be to develop and further work on integrating offshore wind and O&G regions into the TIMES model. Whereas, the aim will be to develop a novel approach that implements offshore O&G - and wind regions into the TIMES model.

Chapter 3

Objectives of the Study

3.1 Problem Definition

In order to achieve the climate targets, it is necessary to reduce emissions in the petroleum sector, while ensuring energy security and sustainability. This thesis aims to explore the feasibility and potential of electrifying the petroleum sector to mitigate its impact on the energy system. The study will analyze the integration of offshore wind, and power from shore to determine the most cost-effective solution for reducing emissions and transitioning to a more sustainable energy system.

A TIMES energy system model of the Norwegian power system (IFE-TIMES-Norway) has been modified with additional regions to answer the research questions of this study. Model development includes improved representation of the offshore regions and the electrical trade between mainland and offshore regions. The offshore regions should represent potential wind power production and O&G platform demand.

The final model that includes both mainland and offshore regions allows for exploring and assessing future electrification scenarios on the Norwegian continental shelf(NCS). As a result of the updated energy system model, imports and exports of electricity between regions will be examined along with potential emission reductions with the most cost-effective solutions for electrifying the NCS will be evaluated.

3.2 Research Questions

This master's thesis will investigate the following research questions:

RQ1: What are the potential for CO_2-emission reductions by electrifying the platforms with offshore wind energy and/or power from shore?

RQ2: How do the offshore wind resources differ across the Norwegian Continental shelf and how do they match the demand of offshore O&G platforms?

RQ3: What are the most cost-efficient solutions for decarbonizing the oil and gas industry in Norway?

RQ4: How is the Norwegian energy system impacted by electrification and large-scale offshore wind production (e.g., electricity prices, export volumes, and land-based RES production)?

3.3 Limitations

To limit the scope of the master thesis, only electrification from offshore wind and power from shore is implemented into IFE-TIMES-Norway as an electrification opportunity throughout this master thesis. This is based on current technology and is considered the most relevant. Additionally, only evidence bases and reports published at the latest by February 2023 have been considered. The literature states that gas turbines will be required as backup when offshore wind is used to supply oil and gas platforms. However, the study's main limitation is that the temporal resolution does not capture the fluctuations in offshore wind detailed enough.

Chapter 4

Theoretical Background

This chapter is intended to provide a theoretical background to the IFE-TIMES-Norway model, oil and gas fields, offshore wind power, and shore power.

4.1 Introduction to IFE-TIMES-Norway

IFE-TIMES-Norway was developed jointly by the Norwegian Water Resources and Energy Directorate (NVE) and the Institute of Energy Technology (IFE), in which the modeling framework was developed by ETSAP (the Energy Technology Systems Analysis Program) based on the IEA(International Energy Agency) agreement. The model is a detailed long-term optimization model of the Norwegian energy system that is generated by TIMES (The Integrated MARKAL-EFOM System)[35]. TIMES is based on the modeling language General Algebraic Modelling System (GAMS). To achieve a deeper understanding of the IFE-TIMES-Norway and its function, the next section presents two important aspects: linear optimization and the structure of the model. This will provide greater insight into how the model operates and simulates long-term energy scenarios.

4.2 Linear Optimization

There are three types of entities in a linear optimization problem formulation in TIMES[30]:

- *Decision variables*: In optimization, decision variables represent unknown quantities or endogenous quantities that need to be determined by the optimization.
- *Objective function*: Criterion to be minimized or maximized.
- *Constraints*: Inequalities or equations involving decision variables that the optimal solution must satisfy.

A set of linear programming equations and variables underlie the TIMES model. The fact that TIMES outputs are linear functions of its inputs and that non-linear functions can also be represented as stepped sequences of linear functions means that all equations in TIMES in principle are linear functions[36]. A linear programming problem can be used to calculate partial equilibrium due to this linearity property. Linear programming is a mathematical method used to optimize the solution to a linear problem under given constraints. The canonical form of linear programming can be expressed as follows[30]:

$$Max\ c^{\mathrm{t}}x \tag{4.1}$$

$$Ax \leq b \tag{4.2}$$

$$x \geq 0 \tag{4.3}$$

Where $c^t x$ is the linear objective function to be minimized, x is a vector of decision variables, b is a vector constraint, A is a matrix that represents the constraint coefficient yielding to $Ax<b$ representing various sets of inequality constraints. Constraints are equations or inequalities involving the decision variables that must be met by the optimal solution. Examples of model constraints in TIMES are load profiles, resources, and technology characteristics. Examples of decision variables may be investments and operation variables of the energy system.

The TIMES objective function minimizes the total discounted cost of the energy system to meet the demand for energy services at the least cost over a specified period of time[5][35], while taking constraints into account. The total cost of the energy system includes costs related to investment in both supply and demand technologies, operation and maintenance costs, and income generated from exports and costs from imports of electricity. The TIMES objective function can be expressed in the mathematical formula seen in 4.4 [30].

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \cdot ANNCOST(r, y) \tag{4.4}$$

Where,

- NPV is the net present value of the total cost for all regions and all periods.
- region r and year y.
- ANNCOST is the total annual cost.
- $d_{r,y}$ is the discount rate.
- YEARS is the set of years on the horizon.
- R refers to the set of study regions.

4.3 Model Structure

A schematic view of the structure of IFE-TIMES-Norway is illustrated in figure 4.1, with general inputs and outputs. The exogenous input data contains e.g. demand for various energy sectors, technology data, and demand profiles. Model outputs may be technology investments, emissions, or sources of energy supply mix. The model input data is structured into different Excel files. Figure 4.2 shows an overview of the VEDA interface, with the various category files that are used to input data into the model. SysSettings consists of model characteristics such as base year, time periods, units, etc. While the 6 files to the left represent the base files of various end-use sectors and "Norway_Fuels" is where fuels are defined. The two "SUB_RES" files are project-specific scenario files, in which new technologies are defined that have not yet been included in the model. Furthermore, the "Regular scenario" files are also scenario-specific files depending on the planned analysis. The "Trade Scenario" files are used to define trade links and parameters (existing and new). The scenario file "Base assumptions" contains assumptions that are often used in the analyses. which includes energy taxes, CO_2 -price, electric vehicle subsidies, zero emission trucks (EU), growth constraints for new cars, electricity trade prices, and biomass balances. More about the model specifics can be read in [35].

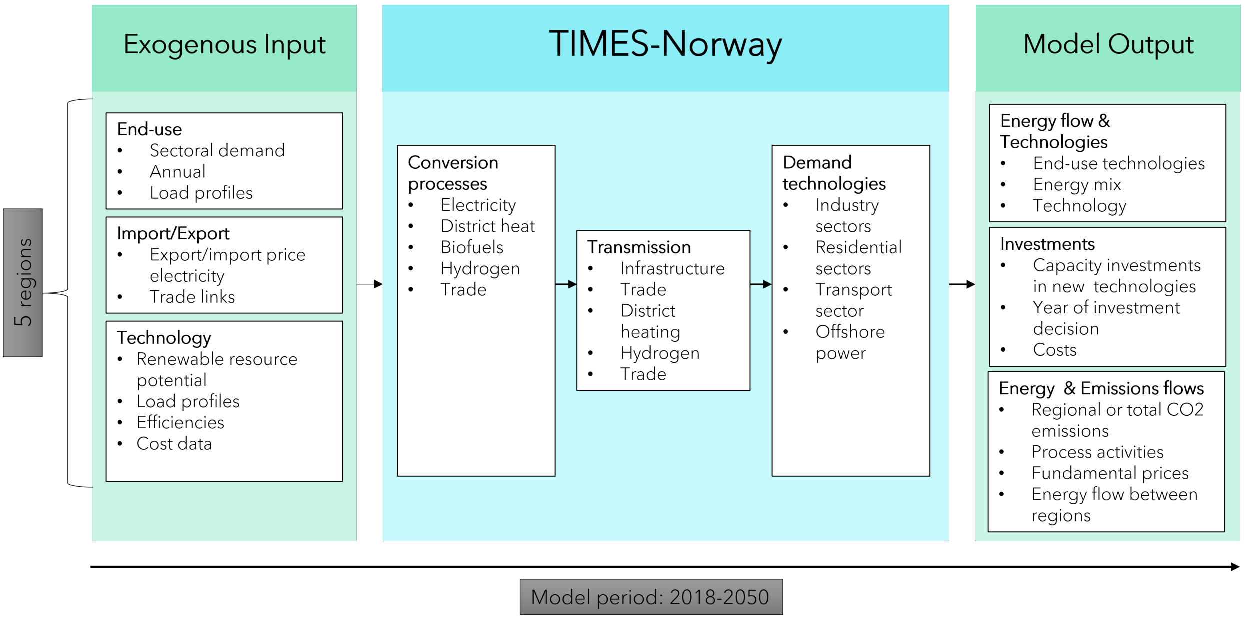


Figure 4.1: Schematic overview of IFE-TIMES-Norway (Figure inspired by [37][35]).

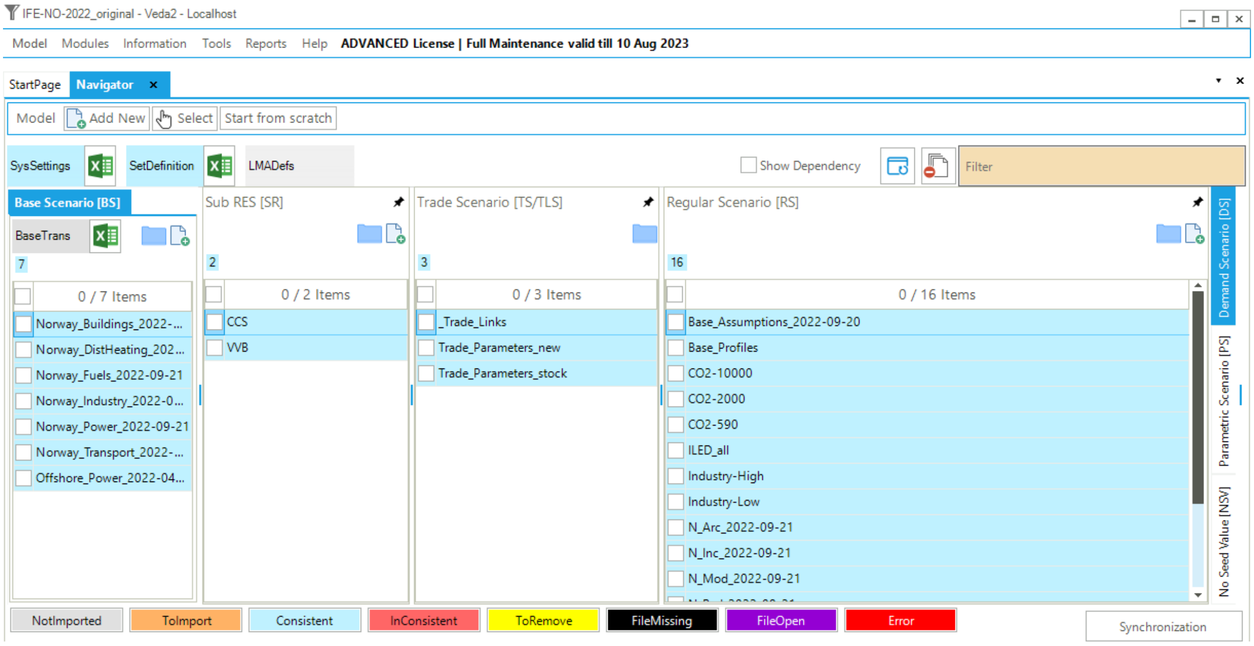


Figure 4.2: Overview of model files within VEDA interface in IFE-TIMES-Norway.

4.3.1 Geographical Coverage

The current model covers the entire energy system of Norway, where all energy use is divided into five spot price regions (NO1-NO5), in which neighboring countries and the surrounding regions exchange flow of electricity. It is important to note, however, that neighboring countries are not included in the IFE-TIMES-Norway spatial coverage as these are exogenously modeled. Additionally, the model consists of six offshore wind regions that are available for investment. The model regions can be seen in figure 4.3. The time horizon of the model is from 2018-2050. Figure 4.4 illustrates how the time resolution is defined in TIMES for all periods[35]. Changing the time slice level is also possible, but this requires more work since different load profiles must also be changed. There are four seasons, where spring is from March to May, summer from June to August, fall from September to November, and winter from December to February, with the total number of time slices being 4 * 24 = 96.

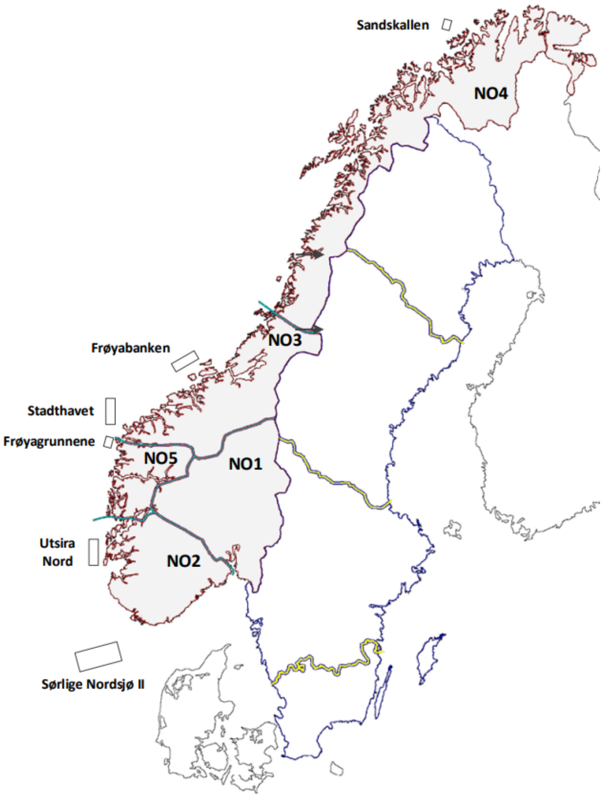


Figure 4.3: Illustration of included model regions: NO1-NO5, and offshore wind regions within IFE-TIMES-Norway model. Image source:[35].

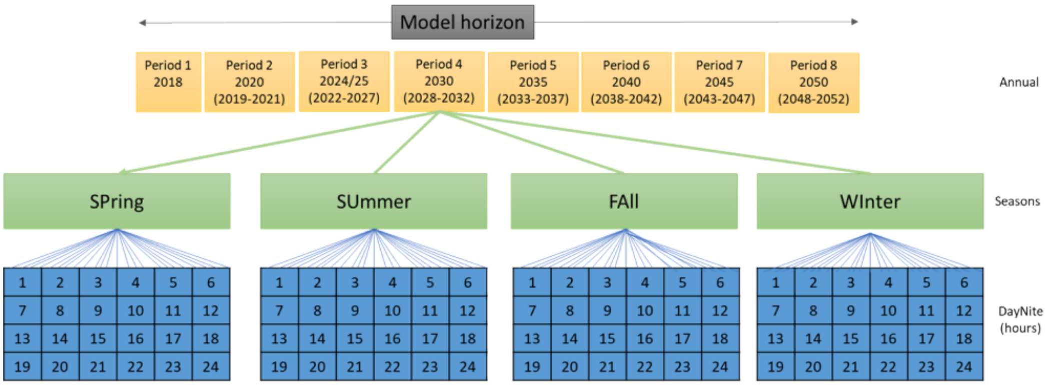


Figure 4.4: The time slice tree for IFE-TIMES-Norway (base version). Image source:[35].

4.3.2 Trade between Regions

The model allows trade between regions and neighboring countries. Figure 4.5 illustrates the excising transmission capacity within Norway and to European countries included in the model. A 20% capacity increase is allowed for trade cables between internal regions in Norway. The IFE-TIMES-Norway model requires exogenous inputs of electricity prices for countries that have transmission capacity to Norway[35]. Table 4.1 shows the average power trade prices exogenous input to the model. The exogenous electricity price is assumed to remain constant after 2040. It is typically project-specific to determine electricity trade prices, but the Base Assumptions file includes a set of prices.

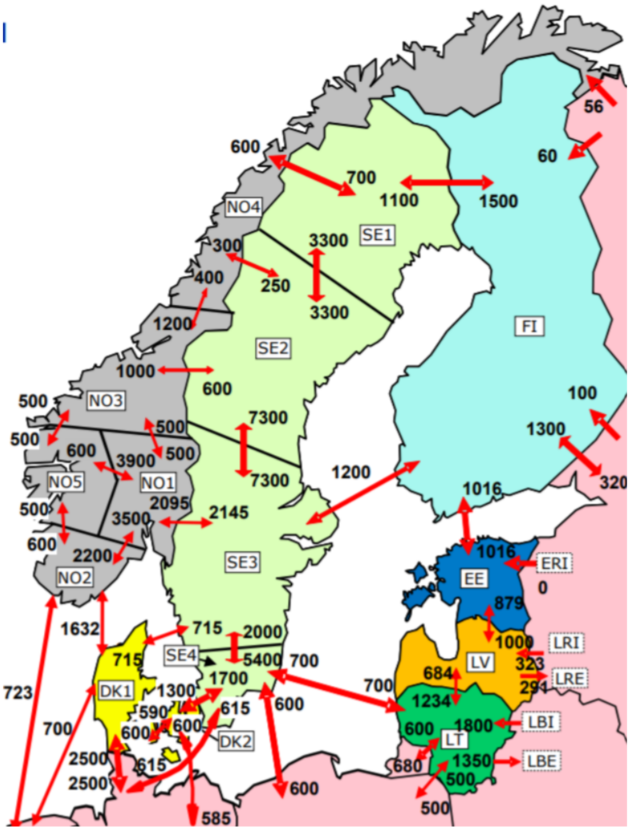


Figure 4.5: Overview of net transmission capacities between regions in IFE-TIMES-Norway. Image source:[35].

Table 4.1: Power trade prices within IFE-TIMES-Norway, NOK/MWh on average[35].

Year	Sweden	Finland	Denmark	Germany	The Netherlands	UK
2022	370	370	350	440	440	540
2025	420	410	430	490	470	560
2030	370	350	470	470	450	480
2040	410	410	440	460	460	510

4.3.3 Petroleum Industry in TIMES

The petroleum sector is currently modeled as part of the industry file, with end-use demand distributed among the corresponding regions NO1-NO5. The petroleum sector is supplied by gas turbines and power from shore. In the model, the existing power from shore demand is included within the associated regions NO1-NO5. However, there are currently no offshore O&G regions, so trade links for power from shore to O&G field are not represented in the model. The model assumes a fixed cost per MW for electrification, regardless of cable length. This means that the model only has the potential of optimizing the region(NO1-NO5) for electrification without specifying the platform and there will also be no difference in which electrification is most cost-effective.

4.3.4 Offshore Wind in TIMES

Currently, the model includes six offshore wind regions connected to mainland regions NO1-NO5. The offshore wind regions are modeled as an investment decision possibility. The offshore wind technology includes the production potentials, limitations, and costs. The costs depend on if the turbine foundation is bottom fixed, or floating, and also if the connection is AC or DC which is affected by the distance between the offshore wind region and the mainland connection. The invested wind park capacity is also influencing the costs.

4.4 Oil and Gas Fields on the Norwegian Continental Shelf

The Norwegian continental shelf covers an area of more than two million square kilometers. The petroleum sector includes all fixed and movable installations on the Norwegian continental shelf that extract oil and gas[9]. It also includes processing and treatment facilities on land (the gas processing facilities on Kollsnes, Kårstø and Nyhamna, Melkøya, and the oil terminals on Sture and Mongstad). At the end of 2022, there were a total of 93 fields in production, of which 6 fields were under development[38]. However, in terms of electrification of the NCS, there are currently 39 main O&G installations on the Norwegian shelf considered relevant. The reason for this is that these 39 main installations are fixed platforms, while the remaining movable installations do not consume constant energy and are therefore irrelevant for electrification projects. In most cases, other platforms or production vessels are interconnected to fixed installations. Figure 4.6 below, illustrates the number of O&G platforms that are expected to be present on the NCS toward 2050 based on decommissioning and planned new fields[9]. There are three main power use areas in a petroleum facility: electricity production, direct equipment operation, and heat generation. A major source of CO_2 emissions from the petroleum industry comes from burning natural gas and diesel in gas turbines. Flaring is also emitting CO_2 but is permitted due to safety considerations. A number of offshore fields and onshore facilities have already been electrified to reduce emissions, and there are plans in place for further electrification with power from shore. As of 2021, the petroleum industry accounted for 12.2 million tonnes of carbon dioxide equivalents[9].

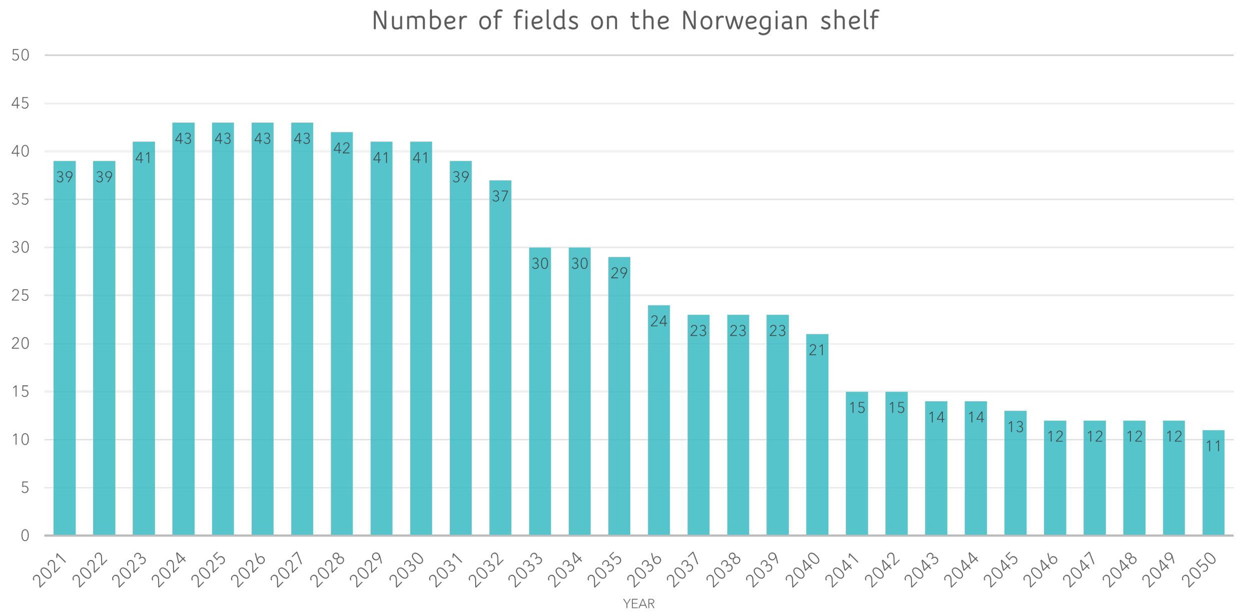


Figure 4.6: An illustration of how many main installation fields that are expected to be present on the Norwegian continental shelf towards 2050, based on decommissioning plans. Planned new production fields are also included.

4.5 Offshore Wind

Norway has among the best wind resources in Europe. As of today, the only offshore wind energy capacity installed in Norway is the Hywind Tampen floating wind park, which provides power to the O&G fields named Gullfaks and Snorre along the west coast. With a production capacity of 88 MW[4], Hywind Tampen will be the world's largest floating wind farm[1]. As a result, Norway is positioned in advance of other countries when it comes to floating offshore wind, despite other countries commitment to more ambitious projects. Figure 4.7 illustrates the offshore wind resources along the coast of Norway and the corresponding ocean depth.

The total cost of offshore wind development depends on a variety of factors. The breakdown of the investment costs in 2021 for a bottom fixed jacket- and floating wind park can be seen in figure 4.8 and 4.9[40]. One of the factors that influence costs and turbine foundation selections include water depth. As floating wind foundations gain their competitiveness at medium water depths, they are used when the area is deeper than 90 meters throughout this thesis[41]. Additionally, the distance between the offshore O&G installation(s) and wind park, influences the technical feasibility in terms of choosing an alternating current(AC) or direct current(DC) connection. Electricity is typically transmitted through DC when distances between shore and production facility exceed 80-150 kilometers[42]. AC transmission has a low station cost, but it is not as effective as DC at long distances[43]. DC is advantageous due to lower cable costs, lower cable losses, and easier offshore installation. Therefore, DC becomes competitive in terms of investment and operational cost if the transmission distance allows for it. Based on internal cost data from IFE, it was calculated that the total cost of offshore floating wind development is almost 40%[40] more expensive than bottom-fixed wind development. According to the estimates, by 2030, investment costs for bottom-fixed wind parks will decrease by 15% and those for floating wind parks will decrease by 35%[40]. Besides the investment cost for the offshore wind park, the wind park system and operational costs also affect the total cost of the wind park project.

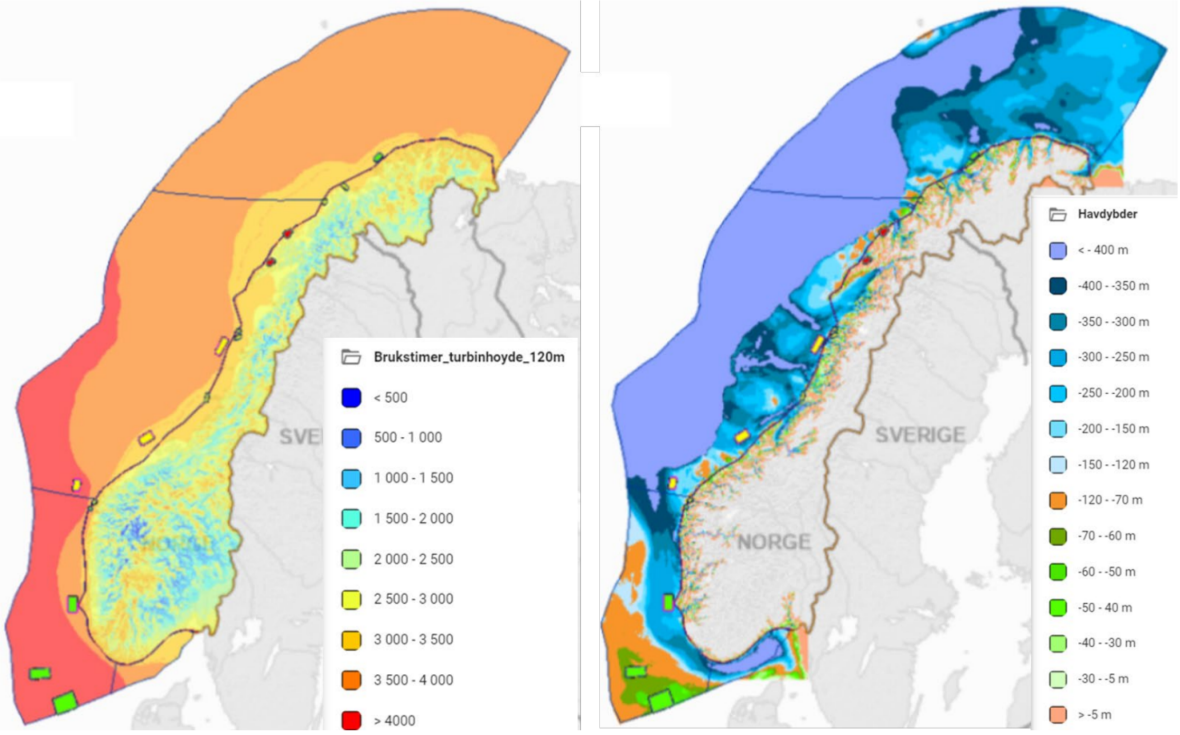


Figure 4.7: Map illustrating wind resources measured in operational hours and the corresponding sea depth (m) along the Norwegian coast. Image source:[39].

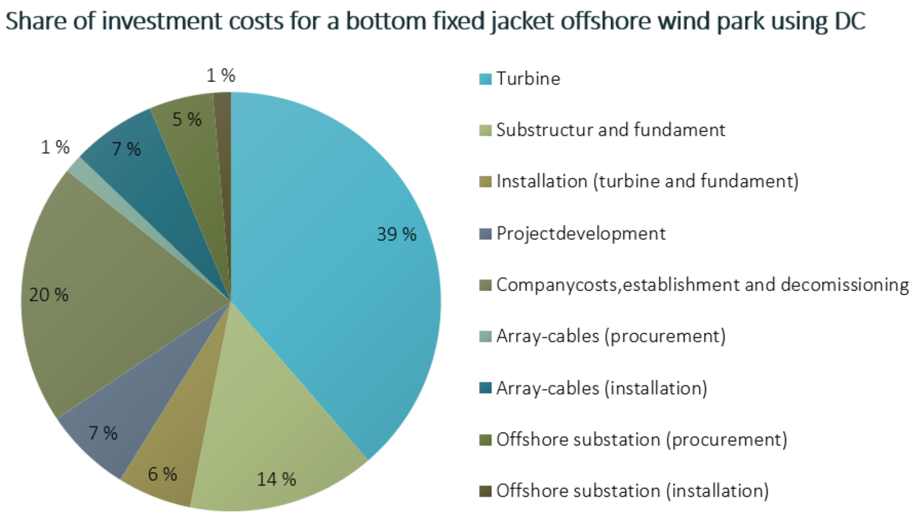


Figure 4.8: Share of total investment costs in 2021 for a bottom-fixed wind park connected to direct current (DC)[40].

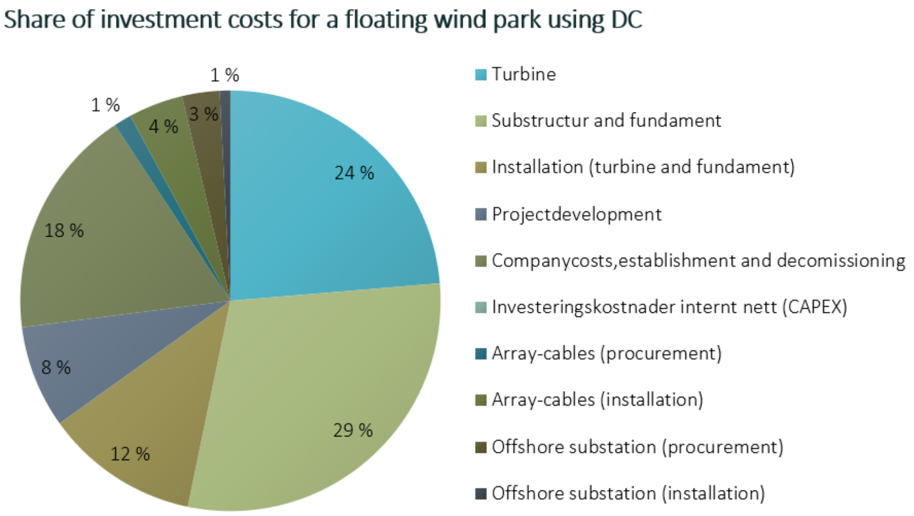


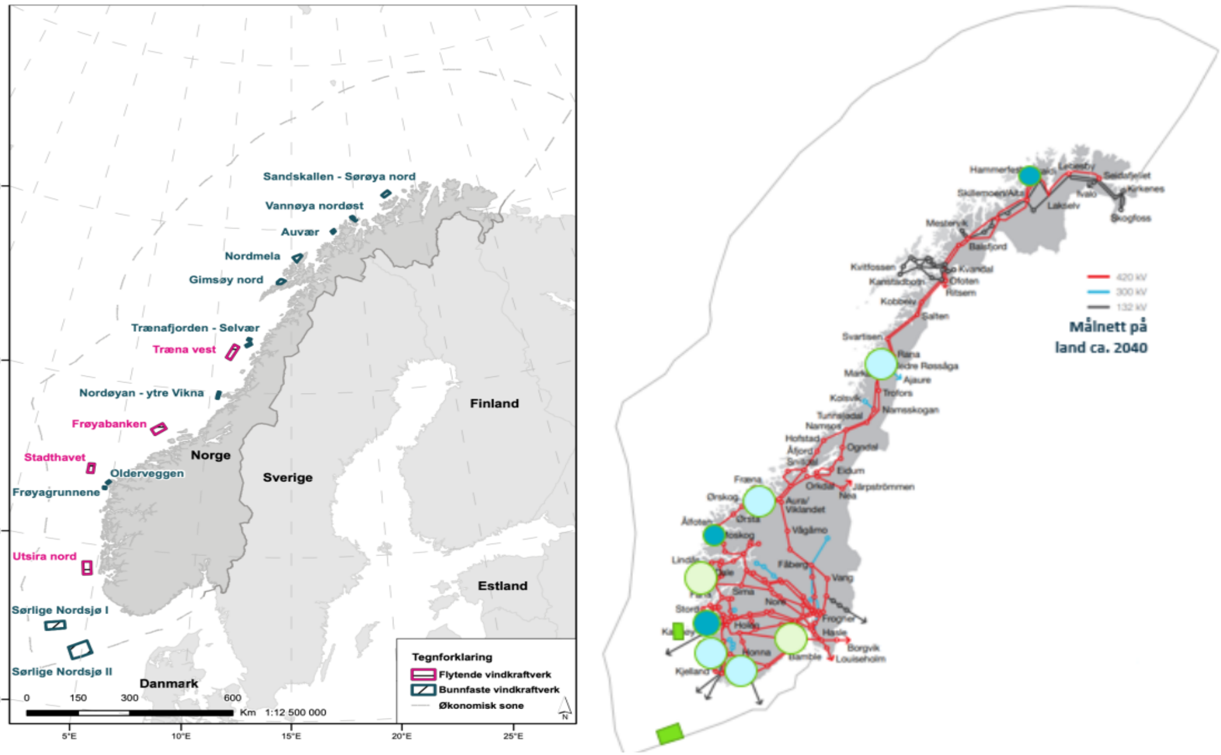
Figure 4.9: Share of total investment costs in 2021 for a floating wind park connected to direct current (DC)[40].

4.5.1 Ambitions

It was announced in May 2022 that the Norwegian Government would update its ambition to assign acreage for 30 GW of offshore wind production by 2040[1]. During the first quarter of 2023, Norway will open two offshore wind farms for licensing applications named Utsira Nord and Sørlige Nordsjø II. Both areas are dedicated to bottom-fixed and floating wind farms with a total capacity of 1.5 GW and the potential for further expansion to 3 GW.

4.5.2 Highlighted Areas

NVE identified 15 possible areas for offshore wind development in Norway in 2012[44]. The areas were selected based on conflict levels with other interests, such as the impact on shipping traffic-, petroleum-, fishing-, and environmental concerns. The offshore wind development areas suggested by NVE can be seen in figure 4.10a, along with the suggested foundation types, bottom fixed in blue and floating wind in pink. Additionally, Statnett recently made further development on recommendations for opening new areas for offshore wind that enable connection to areas with large power demand and capacity in the grid[39]. As a result of a large power deficit and plans for high consumption growth, Statnett rec-



(a) Offshore wind areas. Image source:[44]

(b) Grid connection points. Image source:[39]

Figure 4.10: Identified potential offshore wind production areas by NVE and proposed grid connection points by Statnett along the Norwegian coast for offshore wind production.

ommended building offshore wind with new connections to, especially Grenland and Bergen areas. Volume estimates have also been proposed for connection in 2025 and the years beyond for the various areas. Figure 4.10b illustrates the suggested grid connections for offshore wind development, the potential grid connections can be seen in the colored dots. This study is based on new recommendations of connection areas for offshore wind by Statnett in combination with the study from NVE. At the end of April, NVE will make recommendations for new offshore wind areas based on Statkraft analyses, so the method developed in this study can be used to analyze the electrification of these new areas.

4.6 Power from shore

Power from shore can be used to electrify offshore platforms by replacing the gas turbines on the platforms with underwater cables that supply power generated on shore. Shore power can either be provided by an alternating current (AC) system or a direct current (DC) system[43]. In comparison with DC, AC is easier and less expensive to install, but it is not as effective at long distances[4]. Electricity transmitted by HVDC systems is converted from AC to DC at a mainland installation before being transmitted in cables to an offshore installation. It is then converted back to AC so that power can be used on the platform. Besides the environmental benefits, power from shore can enable higher gas export volumes. A more efficient use of gas resources than burning them in gas turbines on the Norwegian continental shelf is the use of gas in industrial production, households, or electricity generation in Europe[45]. Moreover, Norwegian pipeline gas has a lower carbon footprint than gas imported to Europe from other countries.

Chapter 5

Methodology

As mentioned earlier, this work is a continuing work on the added model functionality developed last semester in IFE-TIMES-Norway. Since then, comprehensive changes and model updates have been made in the model to represent offshore regions more precisely and more accurately.

5.1 The Process of Energy System Modeling

In the process of modeling with TIMES, the goal was to achieve a balance between model accuracy, flexibility, and manageability. Models that include too many details may result in computational time problems, even if they improve realism[36]. Alternatively, a simplified model may not reflect the real-world situation being studied if it is too simplified. For this reason, it was critical to identify the most relevant features to include and aspects that may be excluded. A dependable model should accurately represent the energy system and capture its complex interactions.

The modeling process involved the following steps:

1. Problem description: Firstly, the objectives were clearly identified. Thereafter this step consisted of setting the necessary boundary conditions and ensuring what was needed for the model to achieve its purpose.
2. Collecting, editing, and reviewing data: Collecting data on; platform demand, wind profiles, costs, and emissions. Potential and existing trade links were reviewed and implemented into the model. This information is then organized and implemented into the model along with the next step.
3. Updating and adding both new regions and trade links: Additional offshore regions were added to the model; offshore wind regions and O&G regions.
4. Scenarios: Several scenarios were added to the model to answer the research questions.
5. Verifying the model: Model simulations were done to verify if the model describes the system accurately. Model results were reviewed and cross-checked.
6. Model results: Finally, the results were examined, discussed, and ready to be presented.

Some of the steps mentioned were necessary to repeat.

5.2 Case Study Description

The case study builds on using the modeling tool IFE-TIMES-Norway to improve and model a detailed representation of the Norwegian energy system with additional offshore regions.

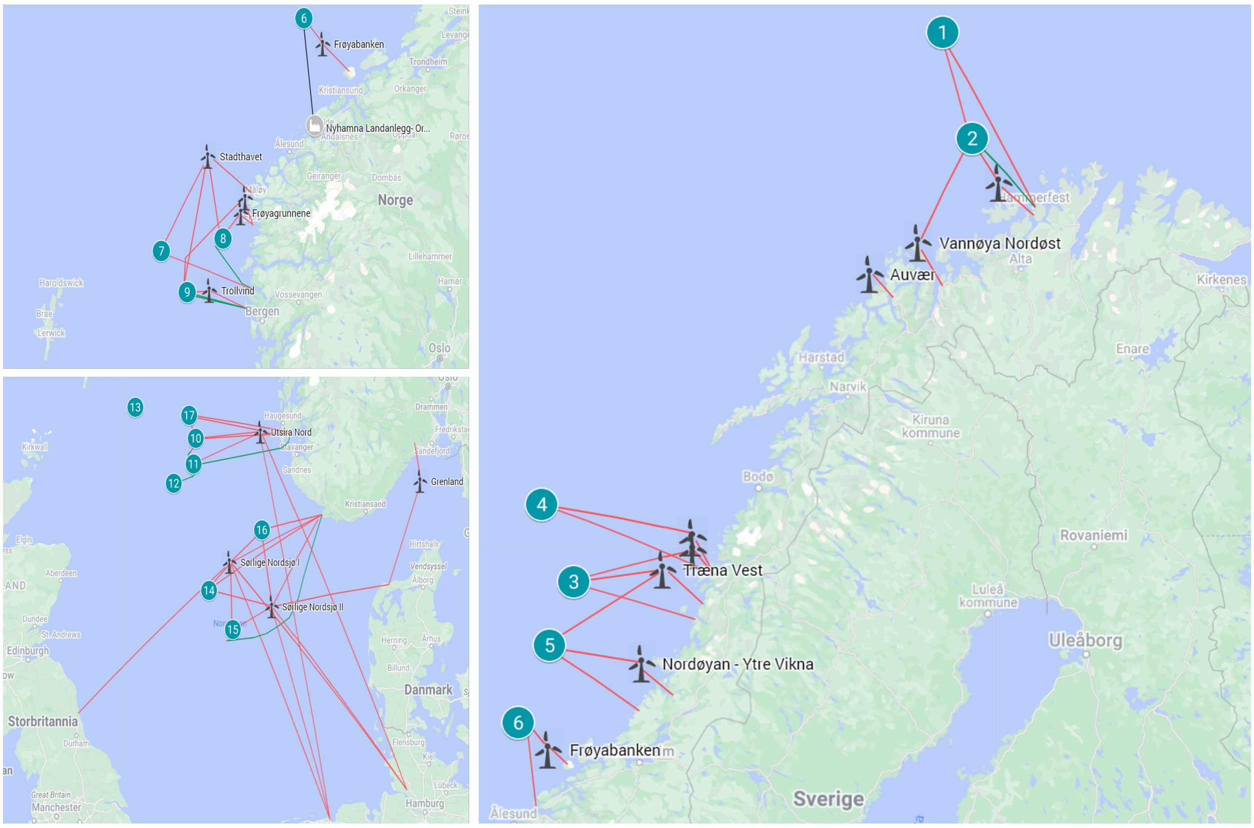


Figure 5.1: Overview of implemented areas covered in the modeling of the Norwegian energy system: O&G groups (green dots with associated O&G group number), wind parks (turbine icon), potential direct and indirect power from shore trade link (red line), excising or decided power from shore trade link (green line).

Figure 5.1 illustrates the additional areas covered in this study. The modeling development in this thesis includes 16 potential offshore wind regions, trade links, and O&G platform groups ranging from G1-G17. Subsequently, the enchanted and modified model is used to analyze electrification scenarios.

5.3 Model Updates and Data Collection

5.3.1 End-use Demand

The end-use demand of the petroleum sector is divided into several O&G groups as new offshore regions. To limit the number of offshore regions, the O&G fields were categorized into 17 groups(G1-G17), in which nearby fields are grouped together. A complete list of the included O&G fields and the associating grouping throughout this thesis can be seen in appendix A, table A.1. Generally, the total oil production on the shelf is steady, since oil production is always ongoing, and demand is therefore assumed to be relatively flat.

The O&G consumption data(end-use demand) that are used as input in this study will be presented. The petroleum sector in this study includes all fixed main oil and gas production installations on the Norwegian continental shelf, along with certain processing facilities. This includes 39 main fields which are assumed to have a constant energy consumption profile throughout the day. Whereas the energy consumption does not remain constant over a year but the daily production profile is. These main fields are connected to satellite fields and subsea installations. There may be combustion from these, but then there will be combustion in connection with drilling activity. Satellites and mobile rigs are not included in the overview for energy consumption. Since it is difficult to find a complete overview of the share of energy demand covered by power from shore and gas turbines for the various platforms on the Norwegian shelf, this had to be prepared to be used as input to the model. The energy demand from today towards 2050 has therefore been developed by using data provided by the Norwegian Environment Agency[46] and Equinor[47]. Additionally, the reports in [8], [9], [4] and the Norwegian Petroleum Directorate was used for data gathering.

The expected energy demand on the NCS towards 2050 is based on current plans and government and industry electrification measures. Demand for 2021 is gathered from the Norwegian environmental agency, but towards 2050 the energy demand for new production platforms increases and decreases in line with decommissioning and new discoveries. A complete list of included O&G fields can be seen in appendix A, table A.1, the consumption data are based on the following assumptions:

- Processing facilities Nyhamna and Melkøya are included.
- Karstø, Kolssnes, Tjeldbergodden, Mongstad and slangetangen are not included.
- In accordance with [9], decommissioning is taken into account.
- The following new production fields were added: Bauge, Breidablikk, Johan Castberg, Nova, Fenja.
- The following O&G discoveries are excluded: Kraftla, Linnorm, NOA, Wisting, which are all in the planning phase for shore-powered development.
- Note that the new fields that are connected to their main field will expire when the entire platform group has reached decommissioning date.

An overview of existing and planned electrification measures included in the prognosis of energy demand can be found in table 5.1. Figure 5.2 shows the total expected energy consumption by source on the NCS towards 2050, divided into the following categories; Power supplied by gas turbines, power from shore operational today, and shore power decided or in the planning phase. It is however important to note that this forecast only includes power from shore in operation today and decided or in the planning-phase stage, further electrification beyond is optimized by the model.

Table 5.1: List of power from shore measures on the NCS included in this analysis.

In operation today	**Decided or in planning-phase**
Utsirahøyden	Troll Vest electrification first step
Valhall	Oseberg
Troll A	Nyhamna basis demand
Martin Linge	Ormen Lange phase 3
Gjøa	Melkøya full electrification
Nyhamna Prosessing facility	Snøhvit
Melkøya LNG facility	Halten South (Draugen, Njord)
Goliat	

To validate the data, the numbers from the base year 2021 were compared to statistics of Norway, seen in table 5.2. The difference in electricity is mainly due to that Kollsnes and Karstø are not included in the calculated values. The difference in natural gas/diesel assumes to be due to the conversion factors used in the conversion from Diesel and fuel consumption to energy consumption in gigawatt hours. According to the government "Perspektivmeldingen", it is expected that the production of O&G will increase toward 2024[48]. Over time, the production will decrease gradually, stating that in 2050 32% of the production level in 2024 will be remaining. Using the available data for each O&G field, the aggregated calculations

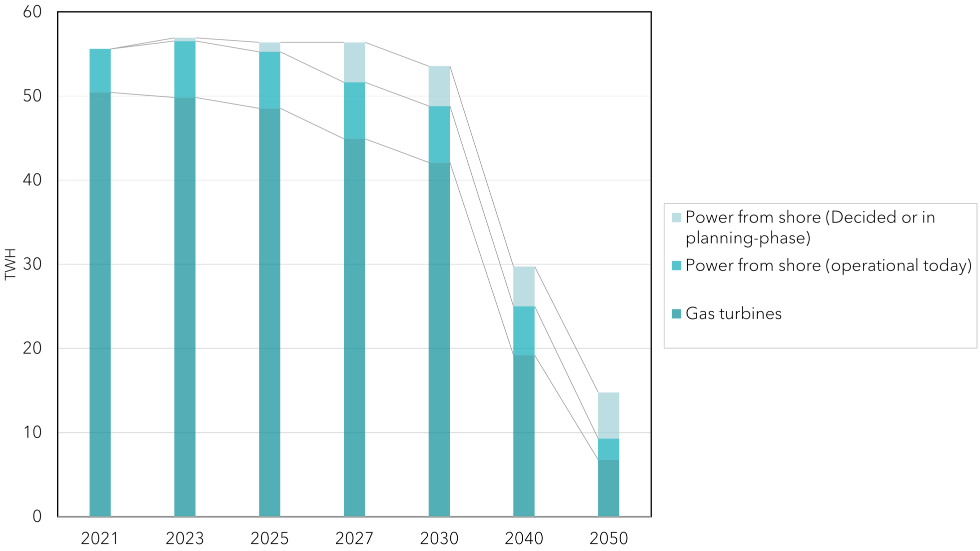


Figure 5.2: Data input to the model. The total energy consumption on the NCS from 2021 - 2050, is divided into the following categories; energy consumption by gas turbines (dark blue), power from shore in operation today (blue), and power from shore plans that are decided or in the planning phase (light blue).

on energy consumption give a 27% reduction in demand by 2050 compared to 2024 levels. Comparing the results shows that the input values used are close to those estimated by the government, and are therefore validated for further use.

Table 5.2: Comparison of calculated values vs statistics of Norway.

	Calculated [TWh]	**Statistics Norway [TWh][49]**
Natural gas/Diesel	50.2	46.14
Electricity	5.2	7.8
Total energy consumption 2021	55.4	53.9

5.3.2 Modelling Offshore Wind Regions

In the previous model version, developed in the pre-project, 8 offshore wind regions were added and modeled based on the wind profiles of the 6 already included wind regions located nearby. To get a more comprehensive representation of the wind power production sites, several updates and changes were made. Realanalysis data of MERRA 2.0 was downloaded and modified for all 8 production sites[50][51]. A Vestas V164 9500 wind turbine is used, along with a hub height of 120 m and data from 2019. The center coordinate of the proposed wind park area was used when collecting data. Furthermore, offshore wind areas were extended to include two new regions, named Trollvind located outside of Bergen, and Grenland. This was done in response to the growing demand for power in those areas as suggested by Statnett[39]. Figure 5.3 shows an overview of all offshore wind regions within IFE-TIMES-Norway including the 8 updated wind regions, the 6 already included, and lastly the 2 new offshore wind regions recommended by Statnett. Each wind park was modeled with a maximum capacity constraint. The total allowable investment capacity in 2030 is limited to 3 GW, in 2035 it increases to 14.6 GW, and 32,6 GW by 2040. The invested capacity is optimized by the model depending on its cost-efficiency.

The following assumptions were made when assessing offshore wind areas and capacity allocation.

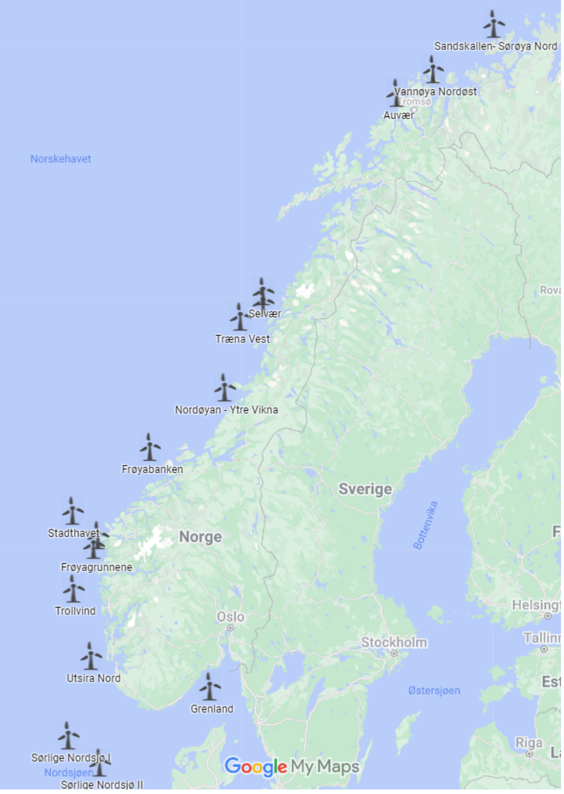


Figure 5.3: Illustration of included offshore wind regions within IFE-TIMES-Norway model.

1. All connection areas recommended by Statnett are linked to the nearest offshore wind farm(s) proposed by NVE along with the corresponding volume that is recommended.

2. Offshore wind development takes time, and commissioning cannot begin immediately after concessions are awarded. Based on this, it is assumed that it takes about 5 years from approval to the commissioning of an offshore wind farm. As a result, no new production is expected before 2030, and as an example, any plans that Statnett has for 2030 are unlikely to be realized before 2035.

3. Numbers for 2030 are based on:

    - Concessions for Sørlige Nordsjl II and Utsira Nord will be announced and granted for a total of 3 GW.

4. Numbers for 2035 are based on:

    - Offshore wind areas planned to be awarded from 2025 are expected to be commissioned from 2030 in parallel with the expansion of the mainland power grid.
    - The volume increase from 2030 is dependent on Statnett development of the power grid as described in the report[39].

5. Numbers for 2045 are based on:

    - Sørlige Nordsjø has a total potential of 9 GW offshore wind.
    - Assuming a linear increase towards 2045 from 2035.
    - A total wind capacity of 32.6 GW by 2045 is based on the Government's goal of announcing 30 GW by 2040.

An overview of the wind park capacity, their corresponding average capacity factor, and the suggested transmission connection nearby can be seen in table 5.3.

Table 5.3: Overview of offshore wind capacity distributions for included wind areas, and their respective average capacity factor and nearby grid connection point. Modeled as upper bound constraints for maximum allowable offshore wind investments based on NVE 2012[44] and Statnett 2023[39].

Wind Area	**Avg.CF [%]**	**Max capacity [MW]**			**Nearby grid connection**
		2030	**2035**	**2045**	
Sørlige Nordsjø II	57	1500	2800	5600	Sørlandet
Sørlige Nordsjø I	50	0	0	3400	Sørlandet
Utsira Nord	47	1500	3600	7200	Stavanger, Haugalandet
Frøyabanken	42	0	2000	4000	Romsdal
Sandskallen	39	0	500	1000	Hammerfest
Frøyagrunnene	48	0	200	400	Ålfoten
Olderveggen	47	0	200	400	Ålfoten
Stadthavet	48	0	300	600	Ålfoten
Trænafjorden	42	0	300	600	Rana
Selvær	45	0	300	600	Rana
Træna Vest	44	0	800	1600	Rana
Trollvind	51	0	1400	2800	Bergensområdet
Grenland	37	0	1400	2800	Grenlandsområdet
Vannøya Nordøst	37	0	250	500	NVE area
Auvær	38	0	250	500	NVE area
Nordøyan - Ytre Vikan	43	0	300	600	NVE area
Total max capacity [MW]		3000	14600	32600	

Wind production profile

The realanalysis wind data of MERRA 2.0 was modified to the slice level used in TIMES for all wind production sites. Each season is then represented by one day in the wind production profile input into TIMES. As a result, the wind data captures hourly variations within a day and seasonal variations. Figure 5.4 illustrates the normalized capacity factor for Sørlige Nordsjø I.

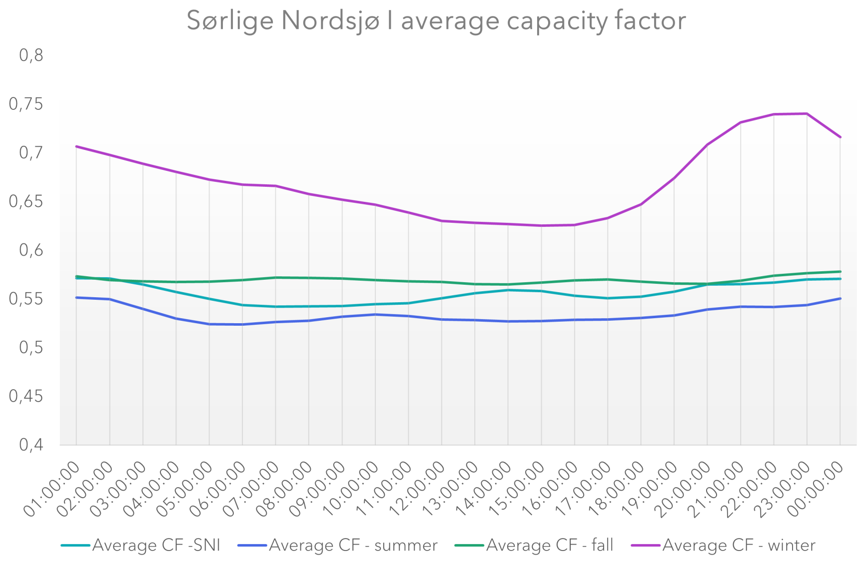


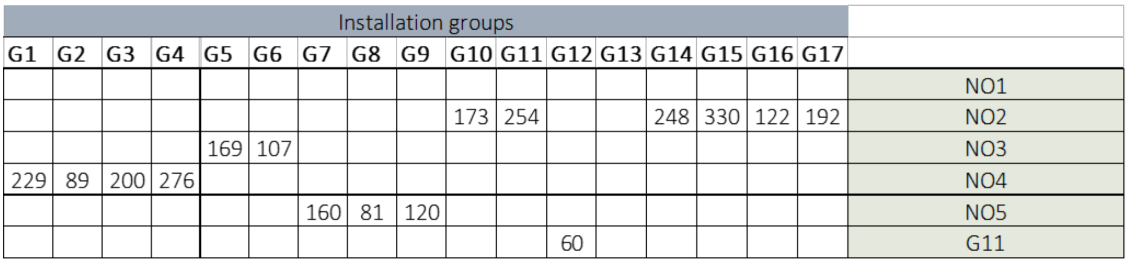
Figure 5.4: Illustration of the normalized average capacity factor for each hour in a representative day for each season at Sørlige Nordsjø I.

5.3.3 Modelling Trade links

The opportunity to electrify O&G groups is enabled through trade links. Trade links are the link between the various model regions. Modeling trade links differentiates existing cables, new cables, and transmission cables to Europe, including investment and operational costs, as well as existing capacity or maximum potential for developing new capacity. In this file, all operational, planned, and decided power from shore cables are included, so that it does not represent an investment opportunity, but rather are included as stock. Whereas, the respective capacity to the existing transmission cable is added as stock. The implemented trade links can be categorized into the following types;

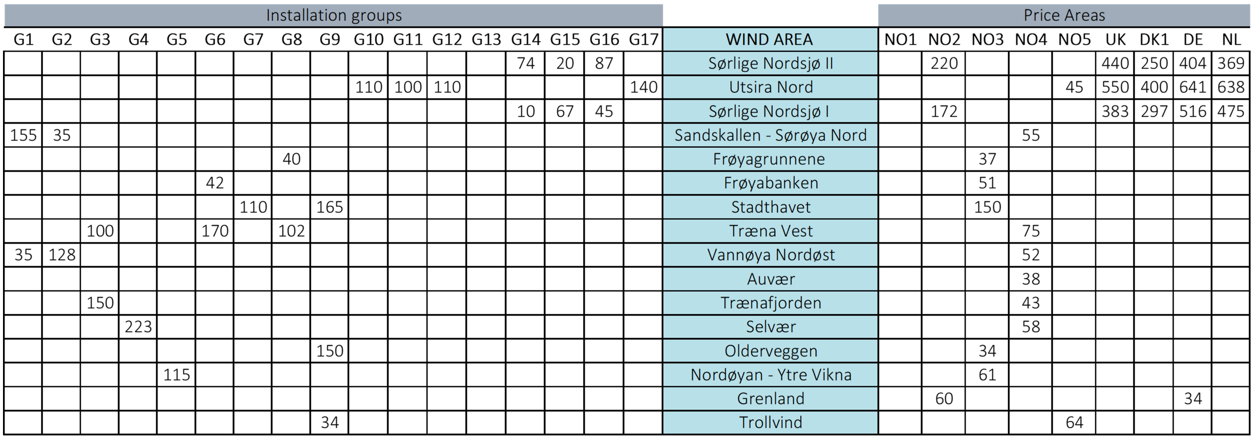
- Direct electrification trade link: NOx-Gx
- Offshore wind electrification trade link: WIND-Gx
- Offshore wind to the mainland: WIND-NOx
- Offshore wind export to Europe: WIND-EU

Figure 5.5 shows a list of all interconnections available for investments in direct power from shore, whereas the number represents the distance in km between the connection points. The model, for instance, would have to invest in a 229 km cable from NO4 if it invested in power from shore to supply platform group G1. While figure 5.6 shows a list of possible trade link connections available between offshore wind area and O&G installation group or price area on the mainland. As seen in the figure, in the model, it is assumed that only Sørlige Nordsjø I, Sørlige Nordsjø II, Utsira Nord, and Grenland can export power to Europe. This was assumed due to the long distance from other offshore wind areas.



Installation groups																	
G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	
																	NO1
									173	254			248	330	122	192	NO2
				169	107												NO3
229	89	200	276														NO4
						160	81	120									NO5
											60						G11

Figure 5.5: Potential tradelinks for direct electrification with power from shore, and the associated distance between mainland regions (NO1-NO5) to O&G groups (G1-G17).



Installation groups																		Price Areas								
G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	WIND AREA	NO1	NO2	NO3	NO4	NO5	UK	DK1	DE	NL
													74	20	87		Sørlige Nordsjø II		220				440	250	404	369
									110	100	110					140	Utsira Nord					45	550	400	641	638
													10	67	45		Sørlige Nordsjø I		172				383	297	516	475
155	35																Sandskallen - Sørøya Nord				55					
							40										Frøyagrunnene			37						
					42												Frøyabanken			51						
						110		165									Stadthavet			150						
		100			170		102										Træna Vest				75					
35	128																Vannøya Nordøst				52					
																	Auvær				38					
		150															Trænafjorden				43					
			223														Selvær				58					
								150									Oldervеggen			34						
				115													Nordøyan - Ytre Vikna			61						
																	Grenland		60						34	
								34									Trollvind					64				

Figure 5.6: Potential tradelinks between the offshore wind areas, with associated distance in km between the regions.

5.3.4 Modeling of Costs

Modeling of cost is an important part of the method since the model aims to minimize the total cost of the energy system. In this case, the cost of offshore wind investments, power from shore, and CO_2 tax are considered relevant.

The costs related to developing each offshore wind park were included exogenously in the model files within TIMES. Offshore wind investment costs are based on data provided by IFE, where the investment cost of a specific offshore wind farm is specified and calculated based on the wind farm capacity, type of structure, and connection type (AC or DC). The operational cost of the wind farm is assumed to be 1% of the total investment cost. Grid investments regarding grid connection between offshore wind, O&G regions, NO regions, and Europe were calculated using IFE base data and calculating for the specific transmission cable. Grid investment costs are influenced by the distance between the connection points, the type of connection, and the planned cable size. The breakdown of the offshore wind investment costs used as input was presented in section 4.5, figure 4.8 and 4.9. The CO_2 tax development used in the modeling is based on table 5.4, which is based on the government plan for a tax of 2000 NOK/ton in 2030[18].

Table 5.4: Overview of the CO_2 tax values used for all modelled scenarios in IFE-TIMES-Norway.

Year	Tax [NOK]
2020	590
2030	2000
2040	2960
2050	4382

5.3.5 Modeling of Constraints

Through modeling, it was necessary to make assumptions and impose constraints. Figure 5.7 provides an overview of the key constraints incorporated into the model. These constraints are common to all scenarios that were modeled. Nevertheless, the constraint is only applicable if the technology is included in the scenario. For instance, since ONLYPFS scenario only has one option for electrification with power from shore, the available year for investments in offshore wind is irrelevant for that scenario.

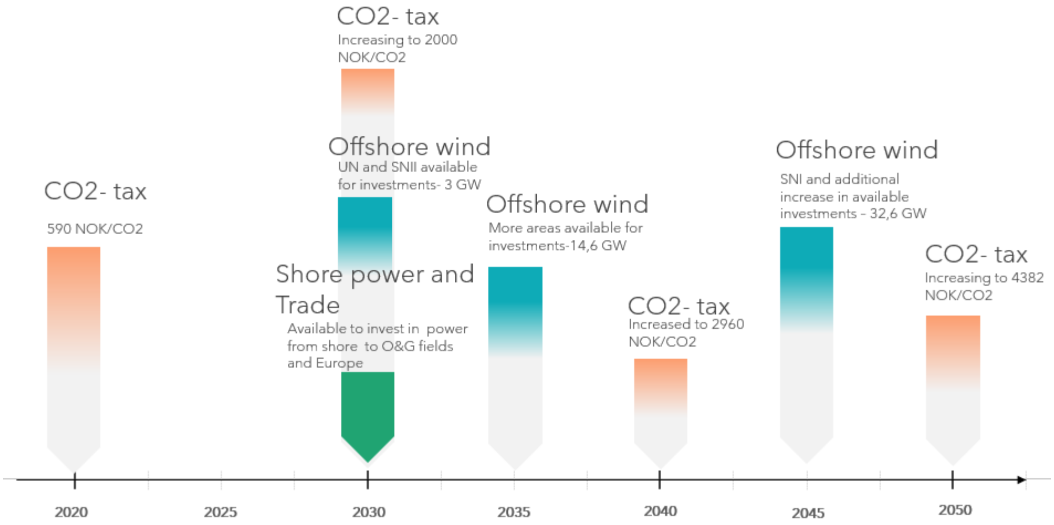


Figure 5.7: Modelling timeline including the available start date of investments and key modeling constraints.

5.4 Scenarios

To answer the research questions of this master thesis, IFE-TIMES-Norway is used to develop a case study with multiple scenarios. All scenarios are based on the current expected energy demand on the NCS towards 2050, previously described in chapter 5.3.1. Moreover, the scenarios assume a moderate level of industrial development seen in [35], whereas new industry development includes new data centers and battery factories. Different electrification alternatives are implemented, whereas some scenarios only offer offshore wind or shore power as an option for electrifying the NCS. An overview of the various scenarios can be seen in table 5.5.

Table 5.5: Overview of modeled scenarios in IFE-TIMES-Norway.

Scenario	Description
NONE	No electrification allowed
LIMITED	Limited electrification following 55% emission reduction pathway to 2030[52]
COMBINATION	Free use of electrification option
ONLYPFS	Power from shore is the only electrification option
ONLYOW	Offshore wind is the only electrification option

NONE Scenario

NONE scenario represents a scenario where no electrification of the O&G fields is allowed, except for the electrification already in operation or planned. In addition, offshore wind investments for other purposes are not permitted.

LIMITED Scenario

The LIMITED scenarios follow the most optimistic emissions pathway suggested by "Norsk klimastiftelse" [52] to reach a 55% emission reduction compared to 1990 levels and by net-zero emissions in 2050. The allowable investment in electrification technology equals the amount which corresponds to the emission pathway just mentioned. In the LIMITED scenario, the model has the opportunity to electrify the oil and gas demand with both offshore wind and power from shore. Additionally, offshore wind regions are able to export and import power to/from Europe. This is only an opportunity in regions located in the southern part of the NCS. This gives the model increased flexibility to balance the energy system. Figure 5.8 shows a schematic illustration of the model options in the LIMITED scenario.

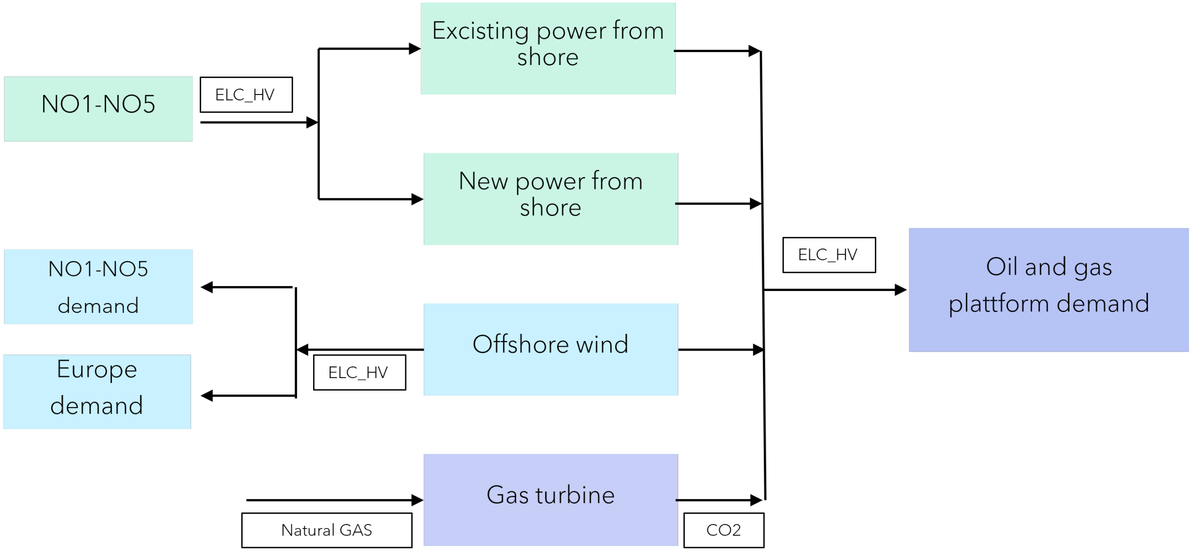


Figure 5.8: A schematic view of options for electrifying the NCS under the LIMITED and COMBINATION scenario.

COMBINATION Scenario

In the COMBINATION scenario, the model has the opportunity to optimize electrification with both offshore wind and power from shore freely. The rate of electrification can therefore differ from the LIMITED scenario. The COMBINATION scenario is based on the same assumptions as the LIMITED scenario, but with no limits on allowable investments in electrification technologies. Therefore, it also explores the most cost-efficient solutions for decarbonizing the petroleum industry. Figure 5.8 illustrates the schematic view of options for electrifying the NCS under the COMBINATION scenario (similar to LIMITED).

ONLYPFS Scenario

In the ONLYPFS scenario, the model only has the option to electrify with power from shore. This scenario also explores how electrification of the overall Norwegian energy system will need to be accomplished without offshore wind. Figure 5.9 illustrates the model options in the ONLYPFS scenario.

Figure 5.9: Illustration of model options in the ONLYPFS scenario.

ONLYOW Scenario

The ONLYOW scenario presents the only opportunity for electrifying the O&G demand using offshore wind, beyond electrification measures in operation or decided today. The purpose of this scenario is to explore the capability of offshore wind alone. The model also has the option of importing or exporting wind power to Europe or the mainland. Nevertheless, the need for gas turbines for hours when the wind is not blowing is not captured due to the coarse temporal resolution of the model. Figure 5.10 illustrates the model options in the ONLYOW scenario.

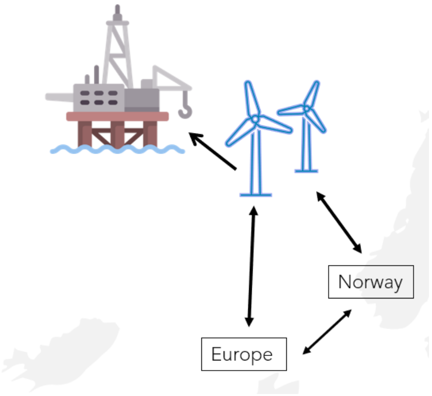


Figure 5.10: Illustration of model options in the ONLYOW scenario.

5.5 Model Validation

One of the most time-consuming aspects of the master thesis was validating the model and the various scenarios. A validation check has been performed to ensure that new regions and changes have been registered and entered in a way understood by the model. Additionally, it was important to define the various scenarios in such a way as to facilitate the exploration of their differences and characteristics in order to answer research questions. Ultimately, the goal of the model was to represent energy scenarios that accurately reflected and incorporated offshore regions within the Norwegian energy system. As part of modeling of the LIMITED scenario, it was particularly important to follow an emission forecast that would provide the reductions in emissions that the government has set as a goal. As a result, the LIMITED scenario is able to provide information regarding how and to what extent electrification is required to achieve the goals. The existence of such scenario will facilitate comparisons with other scenarios, leading to more discussion and, consequently, better outcomes. Upon validation, the following list was reviewed.

1. Has the model been updated to include all new regions?
2. Does the model include dummy variables? (This indicates that something is wrong)
3. Is there any investment in new technologies in the model before 2023? (This is in the past and therefore not realistic)
4. If the model invests in new technology, does it also invest in the associated trade link?
5. Is the regional energy balance equal to zero (In=Out)?

Chapter 6

Results and Discussions

The results of the five simulated scenarios within the IFE-TIMES-Norway are presented in this chapter. The chapter is organized into four main sections that discuss and present the results, each examining the research questions topic chronologically. This is further followed by discussions on the overall effect of the NCS electrification.

6.1 Potential CO_2-emission Reductions

Figure 6.1 presents the total CO_2 emission reductions on the Norwegian continental shelf towards 2050 for the various scenarios. The abrupt stop of some of the scenarios is due to the model period that is defined in the modeling. LIMITED scenario, shown in red, illustrates the CO_2-emission reductions that will be required by 2030 to achieve a 55% reduction compared to 1990 values, and a net-zero reduction by 2050. The results indicate that using power from shore only or combining offshore wind with power from shore offers the most significant reductions in CO_2 emissions, this can be seen in the ONLYPFS and COMBINATION scenario. It is evident from figure 6.1 that electrification with offshore wind alone (ONLYOW) does not achieve required CO_2 reductions by 2030, however, it achieves net-zero by 2050. It clearly shows that no electrification (NONE) is not an option if climate goals are to be achieved.

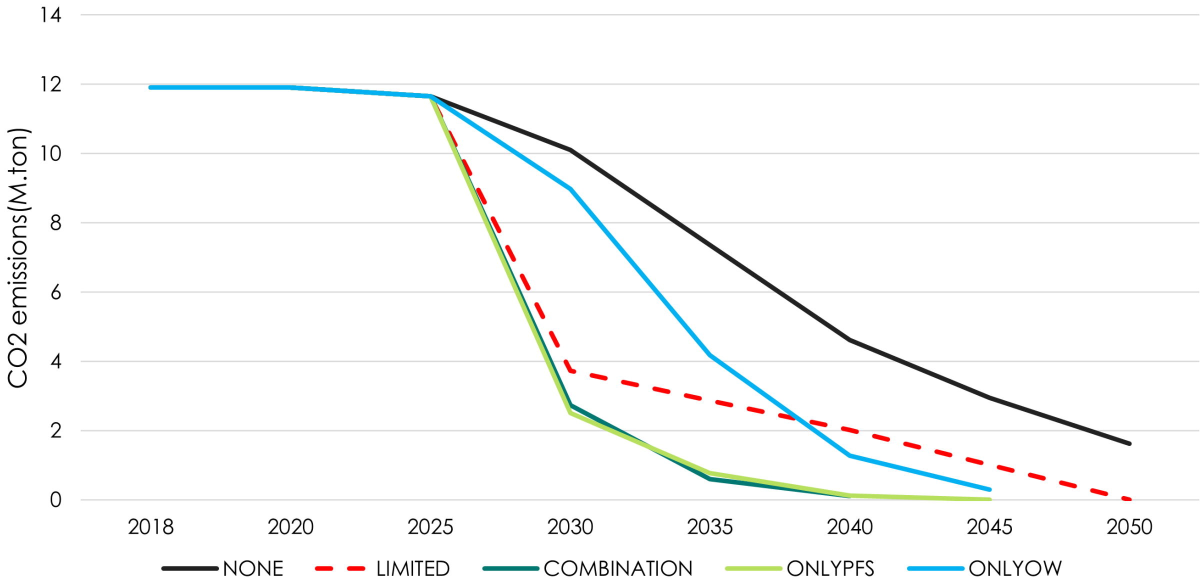


Figure 6.1: Total CO_2 emission reductions on the NCS for simulated scenarios, M.ton CO_2/year.

A reduction in the NONE scenario is expected toward 2050 as a result of decommissioned platforms. Electrification technology investment is limited in the LIMITED scenario, and the allowed electrification corresponds to what is needed to meet the CO_2 targets. In contrast, none of the other scenarios impose any limit on how much the model can invest in electrification technology, apart from the limitation set for offshore wind. Focusing on the main differences between ONLYOW and ONLYPFS, one can see that there is a huge difference in CO_2 emissions reductions by 2030, and that difference is slowly narrowing by 2050. This can be explained by the following; For 2030, offshore wind investments are limited to 3 GW but the model only invests in 1 GW capacity. By not investing in the maximum allowable capacity, the model indicates that it is cheaper to pay the CO_2 tax than invest in offshore wind electrification. As seen from the huge difference in emission reductions by 2030, the model currently favors power from shore as an investment decision in preference to offshore wind. This is assumed since offshore wind investments are also dependent on the demand for power in Norway, as well as technology development, as a result, offshore wind investments will be more favorable later when power demand is higher and the cost of offshore wind is lower. This will be explored further in the following result sections.

Comparing the CO_2 emission development with other studies, figure 6.2 illustrates the CO_2 emission development simulated scenarios compared to historical- and projected emission development by the Norwegian Petroleum Directorate(NPD), Konkraft, and the Energy Agency(EA). As figure 6.2 shows, there are differences between emission reductions from the modeled scenarios and projected emissions in 2030. Moreover, there are some differences in historical emissions for 2018 and 2020 compared to those in the model. This is mainly due to the fact that some onshore plants have not been included in the energy consumption and therefore not accounted for in the model. NPD, Konkraft, and EA emissions in 2030 are higher than those computed by modeled scenarios because they follow the current electrification plans adopted by the government and are therefore within expected limits. In spite of the limitations set in the model and the optimization of the model, the model results in TIMES actually demonstrate a greater emission potential than the expected emission reductions obtained by sources. As a result, it is also evident that large investments in and expansions of the grid are required to meet these objectives. The model does not take into account the queueing system for both accessing large power demand and the installation

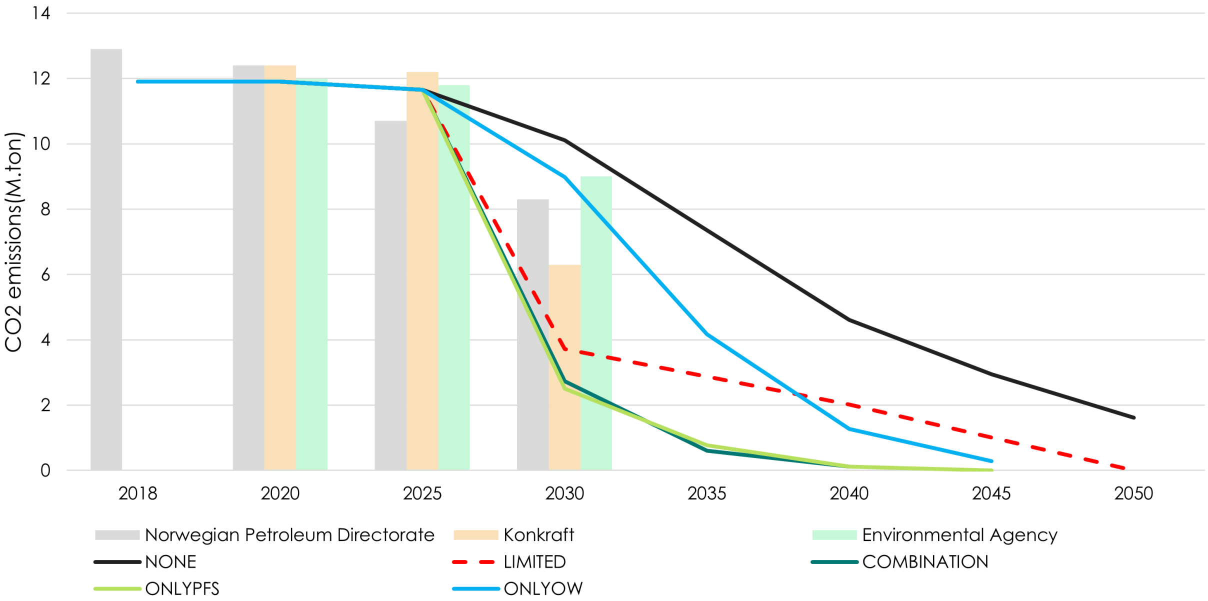


Figure 6.2: Combined CO_2 emission reductions for simulated scenarios on the NCS compared to NPD [53], Konkraft [8] and EA [9] historical emissions and projected emissions, M.ton CO_2/year

of new cables(i.e., competition with other industry sectors) or the distribution network, so it is uncertain whether the emissions reduction potential presented in all the modeled scenarios can be realized as fast as the model proposes. This demonstrates that there will be considerable investment and prioritization required in the queueing system to put in place the electrification at the rapid rate proposed in some of the modeled scenarios. Based on this, an improved model version may be developed by studying how queueing systems work and developing a methodological approach for implementing this into IFE-TIMES-Norway. In the LIMITED scenario, regardless of queueing system, it is interesting to determine how much electrification is required in order to meet the climate goals.

Overall, the model simulations indicate that electrification with PFS or a combination between PFS and OW has the most significant potential to reduce emissions on the NCS. In addition, offshore wind alone has a large potential to reduce emissions from 2035. Nevertheless, emission targets by 2030 are not possible to reach with the government's current offshore wind plans today.

6.2 Offshore Wind Across the NCS

In order to determine whether offshore wind can meet the consumption demands of the NCS, this section will focus exclusively on the ONLYOW scenario.

According to model optimization results, investment in offshore wind energy capacity will increase in the next few decades. Specifically, the model suggests a total investment capacity of about 1 GW in 2030, 8 GW in 2040, and 11.5 GW in 2050. Figure 6.3 illustrates the total offshore wind production (blue bar), the respective offshore wind production used to supply O&G groups (dark blue line), as well as the remaining non-electrified gas consumption (grey bar), the gas consumption that is required to be electrified to fulfill climate targets (orange bar) and lastly the maximum allowable offshore wind production based on government plans in GWh (dashed red line, ref. 5.3).

It can be seen that the maximum allowable offshore wind production based on government plans is much higher than the actual optimized simulated offshore wind production for all years in the ONLYOW scenario. However, the figure indicates that there is insufficient offshore wind production planned by the government by 2030 to meet the government's climate target of a 55% reduction in emissions by 2030 on the NCS. In order to meet this target through offshore wind production, the government should allow for a total wind capacity of at least 6 GW[1], which is currently at 3 GW. However, looking at the figure, it is clear that the model optimization only chooses to produce 34% of the offshore wind production that the government has planned for. The reasons why the model does not utilize the full offshore wind capacity planned by the government can be explained by the fact that TIMES is an optimization model with the objective of minimizing the total discounted system cost, where offshore wind is currently not competitive enough to meet the energy demand of O&G fields and that in 2030, paying CO_2 taxes is a more cost-effective option.

Offshore wind production for supplying the O&G energy demand is projected to increase towards 2040, despite being significantly lower than the available offshore wind production planned by the government. However, it is anticipated that offshore wind production in-

---

[1] Considering a wind park with 4350 operational hours per year[44]. Note that the required wind park capacity change depending on the wind site conditions. Whereas,

$$\text{Required wind park capacity (GW)} = \frac{\text{Energy consumption (GWh)}}{\text{Operational hours (h/year)}}$$

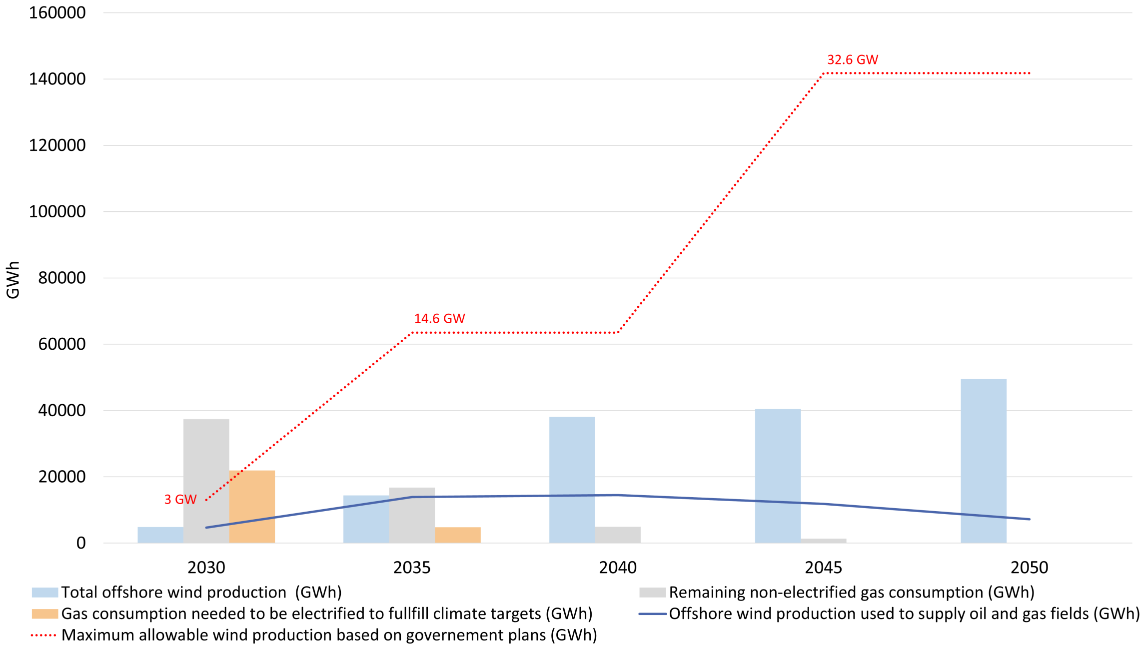


Figure 6.3: Overview of total offshore wind production (light blue bar), wind production used to supply oil and gas fields (blue line), remaining non-electrified gas consumption on the NCS (grey bar), the amount of gas consumption that would need to be electrified to meet climate targets (orange bar) and the maximum allowable wind production based on government limits (dashed red line), GWh/year.

creases towards 2050, but only a relatively small share of the offshore wind production is used to supply the petroleum demand on the NCS between 2040 and 2050, as NCS demand decreases. The model preference for exporting wind power to Europe rather than supplying the entire O&G demand explains the higher total offshore wind production in 2040. Also, the fact that both more wind areas and higher capacities are available for investment. Based on the model results, huge investments in offshore wind will not be profitable to supply electricity to O&G fields toward 2035, which can be seen when comparing the non-electrified gas consumption and the offshore wind production supply to O&G fields. As indicated by the higher total offshore wind production from 2040, investing in offshore wind to supply both demands (to O&G groups and mainland regions) and export potentially can increase profitability. Despite the economic perspective, offshore wind has the potential to meet most of the NCS energy demands between 2040 and 2050, considering both the decline in O&G consumption and the increased offshore wind capacity plans by the government. Offshore wind power, however, will not alone be able to meet the demand needed to achieve a reduction of 55% if the government does not increase capacity announcements in 2030.

However, the limitations of this study include the lack of results regarding the hourly need for gas turbines during hours of low offshore wind energy production. This is mainly due to the time resolution used in the modeling of offshore wind resources. There are several disadvantages to this, including the fact that backup power costs are not properly accounted for as well as the fact that the amount of gas required is not properly understood, as well as whether the wind conditions at the different wind parks used for electrification influence the need for backup turbines differently. As a result, one may underestimate the need for backup power to keep stability, in addition, lack information regarding downtime of the power generation in order to make a comprehensive decision regarding the feasibility of such an investment. As a consequence, this will be an aspect that should be addressed when the model is further developed. Although this limitation exists, the results provide valuable insight into how offshore wind can meet the total consumption demands towards 2050. Also, the following subsection intends to look more closely into the optimal investment selection for offshore wind electrification and the respective demand distribution.

6.2.1 Optimal Investment Selection and Demand Distribution

Figure 6.4 shows an overview of the distributed offshore wind areas proposed by the model optimization to use for electrification to supply petroleum group demand, mainland regions, and Europe connections in the ONLYOW scenario during the modeling period. It can be seen that out of the 16 potential wind areas to invest in, the preferred wind areas are Sandskallen, Nordøyan, Frøyagrunnene, Trollvind, Utsira Nord, and Sørlige Nordsjø I and II. From these wind areas, 10 out of 14 O&G groups are supplied by offshore wind at the latest 2045. As seen in figure 6.4 the offshore wind production sites are evenly distributed across the southwest and west coast, while the remainder of the shelf are having scarcer wind resources allocated based on model investments. Hence, there is less O&G group demand in this area of the NCS. It can also be seen that Sørlige Nordsjø I provides power from wind to the NO2 region, Utsira to NO5, and Frøyagrunn to NO3.

To get a better perspective of how and which offshore wind areas supply the most O&G demand towards 2050, figure 6.5 is illustrated. As seen in the figure, Sørlige Nordsjø II is the only offshore wind area that supplies O&G demand in 2030. In 2035, a total of 6 wind

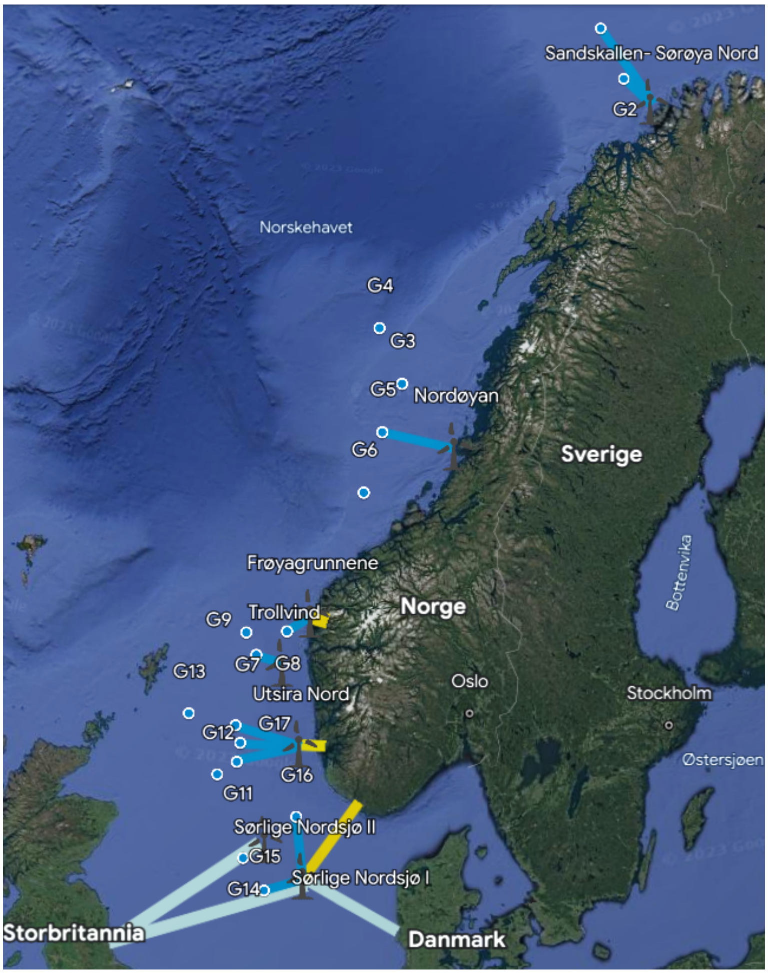


Figure 6.4: Overview of optimized offshore wind electrification sites and associated trade links for the modeling period. Whereas offshore wind electrification to supply O&G demand (blue line), offshore wind to supply the mainland region (yellow), and offshore wind supply to Europe (light blue).

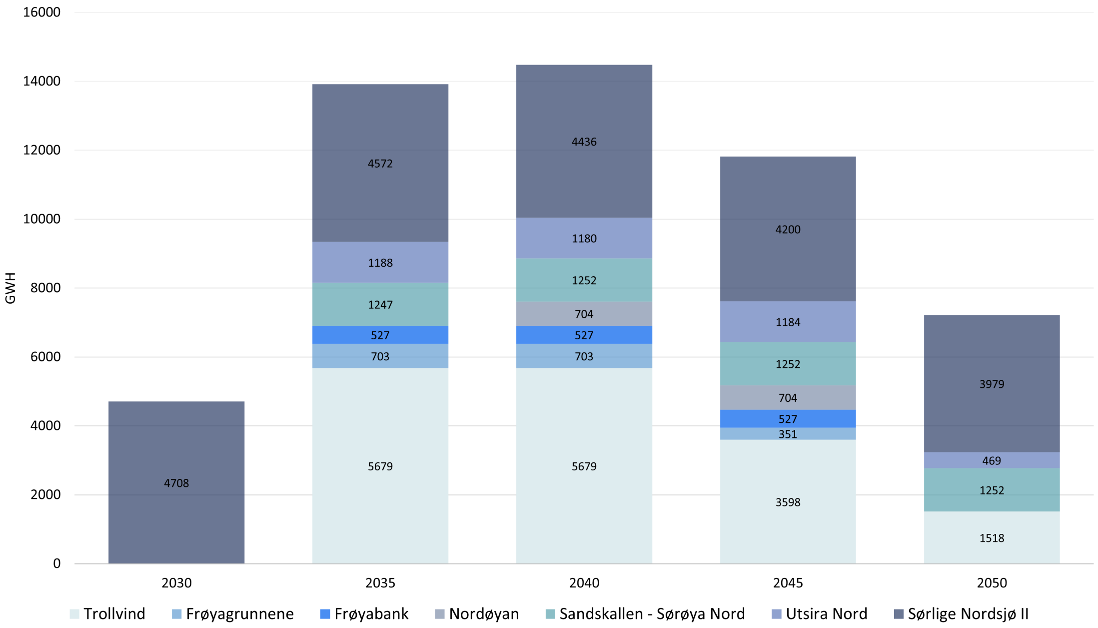


Figure 6.5: Overview of the amount of offshore wind production to supply O&G fields from the respective offshore wind production areas, GWh/year.

production areas are supplying O&G demand, with the majority coming from Trollvind and Sørlige Nordsjø II. A similar demand distribution can be seen for the remaining years till 2050, but with a decreasing trend, as O&G demand is decreasing. It is however noteworthy that the model optimization does not recommend investing in Utsira Nord before 2035, despite the fact that it is one of the two areas that the government plans to open first. Also that Trollvind supply to O&G demand is higher than Utsira Nord. Comparing the two wind production sites, it can be discussed that the higher energy production at Trollvind can be explained by both: The energy demand of G9 alone is more than double the energy demand at each of the three (G17, G11, G10) in total. Additionally, a greater average capacity factor for Trollvind at 51% is obtained, than for Utsira Nord at 47%. Which all are resulting in higher energy production at Trollvind. Both areas supply region NO5, but their shares are relatively small towards 2045, however, by 2050 Utsira Nord will provide 740 GWh (54% of the total wind site energy production). The low share from Trollvind may be because Trollvind has a maximum investment capacity of 1400 MW (according to model limits in 2030-2040) as only 8% will remain after the power used for O&G demand and therefore not sufficient enough to help balance high demand on land. In the event that this limit was increased, it could potentially assist in balancing the power system on land, along with the electrification from Utsira Nord and Trollvind, as having different allocated wind areas with connections to land may have some advantages, as the literature indicates that allocated wind turbines provide a higher level of stability when there is high demand.

As Sørlige Nordsjø II and Trollvind stand for most of the supply to O&G demand, it is interesting to evaluate if the entire offshore wind production is used here. In the Trollvind area, 98% of the production is used to supply O&G demand, while the remaining 2% is supplied to NO5 the entire modeling period. Figure 6.6, shows the share of total offshore wind production at Sørlige Nordsjø II to supply O&G groups and Europe in 2030 and 2045. In 2030, it can be seen that most of the offshore wind production at Sørlige Nordsjø is used to supply G15 demand with 91%, and the remaining 6% and 3% are supplied to G16 and UK. While in 2045 the share of supply has turned drastically, whereas 53% and 42% are used to supply European connections (UK and DE) with power. It appears that the large difference is mainly due to the fact that the model now has the opportunity to invest in more

(a) Sørlige Nordsjø II - 2030.

(b) Sørlige Nordsjø II - 2045.

Figure 6.6: Share of total offshore wind production at Sørlige Nordsjø II to supply O&G groups and Europe in 2030 and 2045.

offshore wind, and the large volumes are due to the fact that producing offshore wind and then selling the power to Europe is profitable.

Due to the way the energy system is modeled, power can flow through the O&G group even though the platform is decommissioned. This allows the decommissioned fields to be repurposed for infrastructure purposes. The platform may be used for green energy production, such as hydrogen or ammonia, or for something else. It can be discussed if this should have been modeled differently since this master thesis does not take into account other electrification than power from shore or offshore wind. This model decision, however, makes it easier to implement new electrification technologies in the future. For clarity, an overall conclusion of section 6.2 is summarised below:

- Offshore wind areas are evenly distributed along the Norwegian coast in relation to where the oil and gas demand is allocated.
- Offshore wind can help balance high power demand on land.
- Investment possibility of both a European connection and electrification of the O&G demand make offshore wind a more profitable investment.
- There are several factors that affect the choice of investments in offshore wind production sites, including the proximity to land/Europe/O&G group, if there is a possibility to connect to Europe, the level of wind resources in the area, the energy demand of the oil and gas industry, and the land-based demand.
- The main limitation of the model results is the lack of results regarding hours when there is low offshore wind production and therefore need for backup power. Despite this limitation, the model provides valuable insight into optimal offshore regions for electrification, and the total NCS energy demand offshore wind can meet.

Results implicitly highlight the importance of accelerating the development of offshore wind, whereas, offshore wind development needs more incentives so that it becomes more cost-efficient and beneficial sooner rather than later, enabling a higher supply to O&G demand to faster electrify the O&G industry, hence reducing emissions.

6.3 Cost-efficient Solutions for Decarbonizing the O&G Industry

6.3.1 Total Discounted System Cost

Table 6.1 presents the total discounted system cost of each scenario as a percentage of the NONE scenario. The actual cost in itself is not particularly informative, and therefore the cost is presented as a percentage to put into perspective by comparing the various scenarios. It is shown that the lowest system cost can be achieved by electrifying with both shore power and offshore wind in the COMBINATION scenario, resulting in a 1.5% reduction from the most expensive NONE scenario. Despite the low percentage difference, this still amounts to a significant sum when the total system cost is high. Considering the increasing high expected CO_2 tax, it appears that the cost of not electrifying the shelf in the NONE scenario is higher than that of electrifying the oil and gas industry. Only electrifying with offshore wind (ONLYOW) is the second most expensive option, which is not surprising based on the model decisions seen in section 6.2. The high costs are due to both high investment costs related to the development of offshore wind, also the fact that the model has no other option to electrify than wind and hence resulting in more CO_2 taxes to pay due to a slower electrification rate than for the other scenarios. To determine which solutions will be the most cost-effective for decarbonizing the oil and gas industry by 2050, the rate of electrification is also important to take into account.

Table 6.1: An overview of the total discounted system costs of each scenario as a percentage of the NONE scenario for the modeling period 2018-2050.

Scenario	**Total discounted system cost [%]**
NONE	100
LIMITED	98.89
COMBINATION	98.62
ONLYPFS	98.86
ONLYOW	99.22

6.3.2 Source of Supply

Figure 6.7 and table 6.2 present the results of the source of supply mix on the Norwegian continental shelf for COMBINATION, LIMITED, ONLYPFS, and ONLYOW scenario. Note that the NONE scenario is not included in the overview because electrification is not possible, therefore gas will be the only energy supply besides existing and planned power from shore. Listed below is a description of the supply source divided into three categories;

- IND-PETRO-ELC: New electrification (Offshore wind and/or power from shore)
- IND-PETRO-ELCX: Planned and decided power from shore
- IND-PETRO-GAS: Power supplied by gas turbines

In figure 6.7, it is interesting to look into the share of electrification technology (IND-PETRO-ELC) that the model optimizes based on the various scenarios, which illustrates what the model chooses to electrify outside its existing electrification plans (IND-PETRO-ELCX). Immediately upon viewing figure 6.7, COMBINATION, LIMITED, and ONLYPFS appear very similar, but ONLYOW shows a striking difference between the share of supply. The main reason for this is the fact that all three scenarios choose to electrify mostly with power from shore, and thus these three scenarios are similar. The ONLYPFS scenario shows the highest share of electrification (IND-PETRO-ELC) with 31.6 TWh in 2030, whereas the ONLYOW scenario shows the lowest share with 4.6 TWh. In the LIMITED scenario, a total electrification of 26.6 TWh is achieved in 2030, beyond the existing and planned power

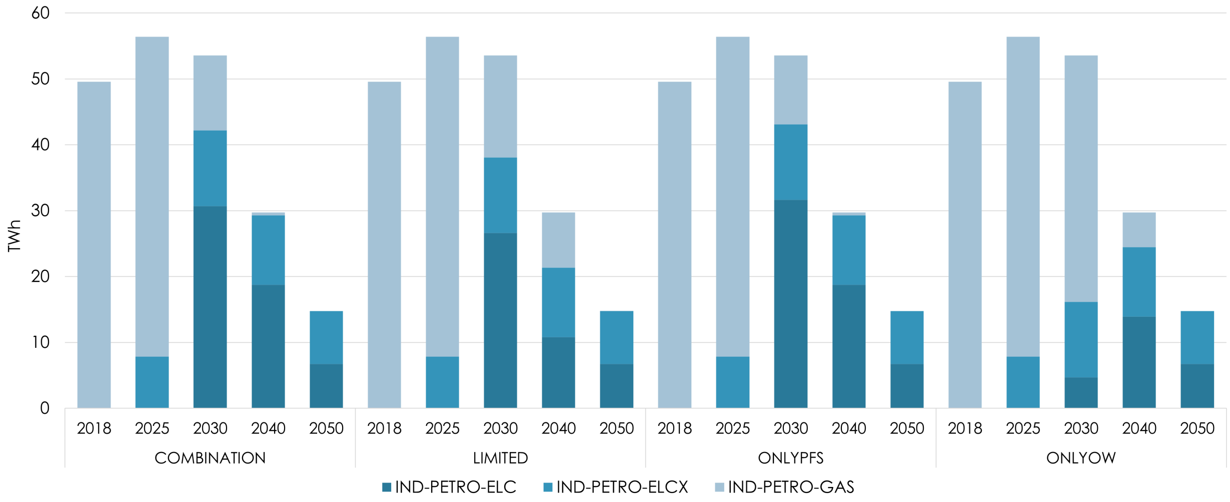


Figure 6.7: Source of supply on the NCS, categorized into IND-PETRO-GAS (light blue), IND-PETRO-ELCX (blue), and IND-PETRO-ELC (dark blue) shown for "COMBINATION", "LIMITED", "ONLYPS" and "ONLYOW" scenarios, TWh/year.

Table 6.2: Distribution source of supply, TWh/year.

	COMBINATION			LIMITED			ONLYPFS			ONLYOW		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
ELC	30.6	18.7	6.7	26.6	10.8	6.7	31.6	18.7	6.7	4.6	13.9	6.7
ELCX	11.5	10.5	8	11.5	10.5	8	11.5	10.5	8	11.5	10.5	8
GAS	11.3	0.5	0	15.5	8.4	0	10.4	0.5	0	37.4	5.3	0

from shore plants at 11.5 TWh. This equals a 55% emission reduction by 2030. In this regard, it is important to emphasize that an increase in electricity demand of 26.6 TWh in 2030 requires a substantial improvement in current grid capacity and may appear somewhat optimistic. It will therefore be interesting to take a closer look at what is required of new transmission cables between the regions (NO1-NO5), which will be examined later in the results. In all scenarios, the climate target is achieved in 2050 due to both the substantial decline in energy demand caused by platform decommissioning and electrification measures. Based on the results, an electricity supply of 6.7 TWh along with existing power from shore is sufficient to reach the goal.

When comparing LIMITED with the other scenarios, it actually turns out that it can be most cost-effective to electrify the oil and gas industry at a faster pace than needed to reach climate targets in 2030 and 2050. This can be seen for COMBINATION and ONLYPFS, here the total system cost is lower than in the LIMITED scenario (ref. 6.1), and at the same time have a higher electrification rate already by 2030 (ref.6.7/6.2):

6.3.3 Offshore Region Analysis

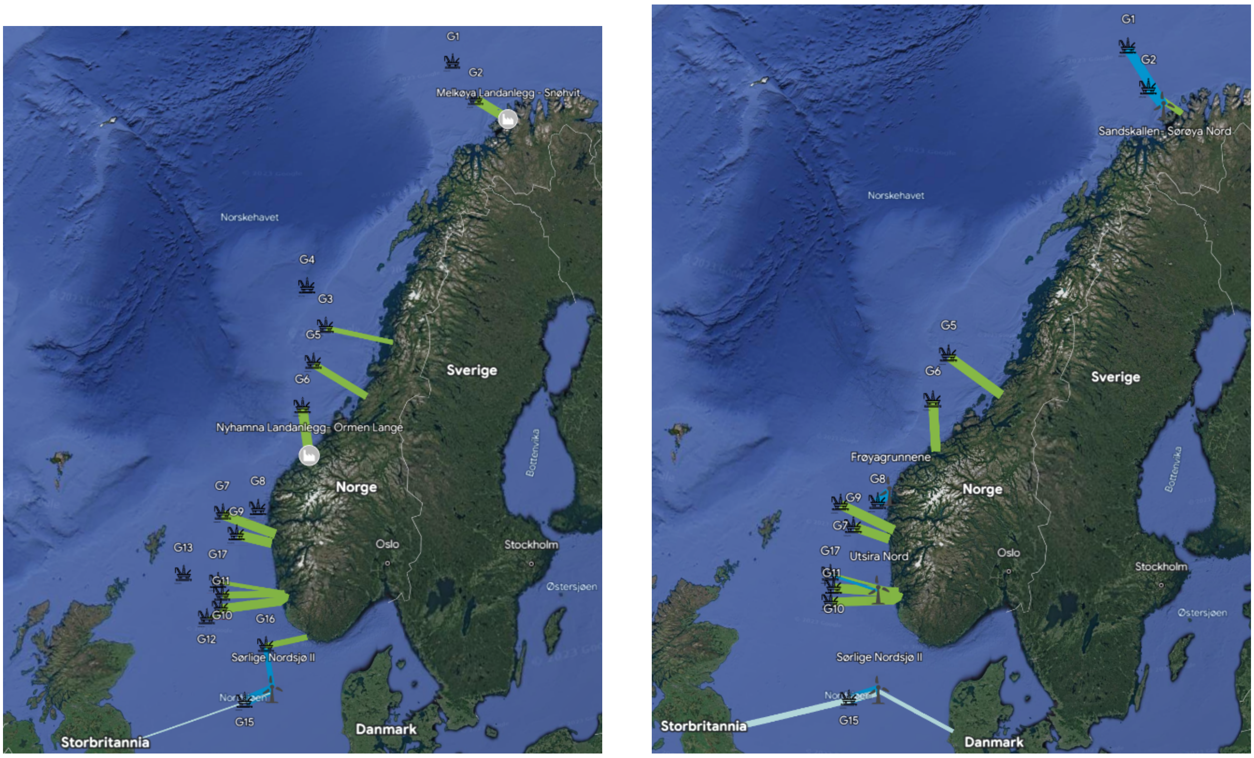
Since the COMBINATION scenario has been shown to be the most cost-effective solution for electrifying the shelf and at the same time reaches beyond the emission reduction target of 55%, this scenario is of great interest to explore in greater detail.

Figure 6.8 shows an overview of electrification decisions optimized by TIMES in the COMBINATION scenario for years 2030 and 2040. Since 2050 is almost identical to 2040, illustrating it is neither interesting nor useful, with the only difference being that 6 more O&G groups are decommissioned. The following can be seen from the figures:

- The green line represents electrification with power from shore.
- The blue line represents electrification with offshore wind.
- The thickness of the line indicates how much of the total energy demand of the O&G group is covered by electricity.
- The overview does not include existing power from shore since this is not optimized by the model and is added exogenously.
- The thickness of offshore wind links to Europe represents the share supplied to Europe connection of total production at the respective wind site.
- Maps have been updated to remove decommissioned platforms.

A clear picture can be obtained from the overview regarding which O&G fields are proposed to be electrified as a result of the TIMES optimization for 2030 and 2040. Upon examining both 2030 and 2040, it is evident that most of the electrification will take place with power from shore. As can be seen, more fields will be electrified with offshore wind power in 2040 than in 2030. A common characteristic of both years is that fields that are electrified are generally those located closest to land.

Figure 6.8a shows that all operating O&G fields in 2030 except 5 fields (G12, G13, G8, G4, and G1) will be partially electrified or fully electrified as early as 2030. In this case, the absence of electrification may be explained by the high distance between the O&G group and the mainland, which makes electrification unprofitable at the time of investment. The model largely electrifies using power from shore rather than power from offshore wind due to the fact that power from shore is a more profitable investment, as mentioned in earlier



(a) Simulated model results for 2030

(b) Simulated model results for 2040

Figure 6.8: An overview of electrification optimization decisions made by TIMES in the COMBINATION scenario. Green line represents power from shore, blue line represents power from offshore wind.

sections. It can also be seen that in 2030, Sørlige Nordsjø II is the only offshore wind farm that supplies part of the O&G demand. According to the figure, G15 will be fully electrified once it is supplied with electricity from offshore wind. Additionally, Sørlige Nordsjø II exports electricity to the United Kingdom. This suggests that investing in offshore wind is more profitable if the model has the ability to sell electricity abroad as well.

Figure 6.8b shows that by 2040, the additional offshore wind areas Utsira Nord, Frøyagrunnene, and Sandskallen are included to supply O&G demand. G1 and G8 are now fully electrified by power from Sandskallen and Frøyagrunnene. The fact that more fields are now being supplied by offshore wind can be attributed to several factors including the availability of more offshore wind areas, the increasing CO_2 tax, and offshore wind investment becoming less expensive. It appears that offshore wind development is the best electrification option when the O&G group is located far away from shore(power from shore becomes too far), as can be seen for G1, G15, and G17 (here distance from shore is between 200-330 km). Nonetheless, offshore wind investments seem to differ somewhat from ONLYOW (ref. figure 6.4) scenario.

Several factors contribute to the selection of offshore wind investment areas:

- Sanskallen does not necessarily has the best wind resources with an average capacity factor of 39 %, but is the wind area located with the best proximity to G1.
- Sørlige Nordsjø I and II have good wind resources as well as being close to Europe and having less than half the distance than if one would connect to shore power.
- Frøyagrunn has close proximity to land and therefore can supply power when there is a high demand on land.

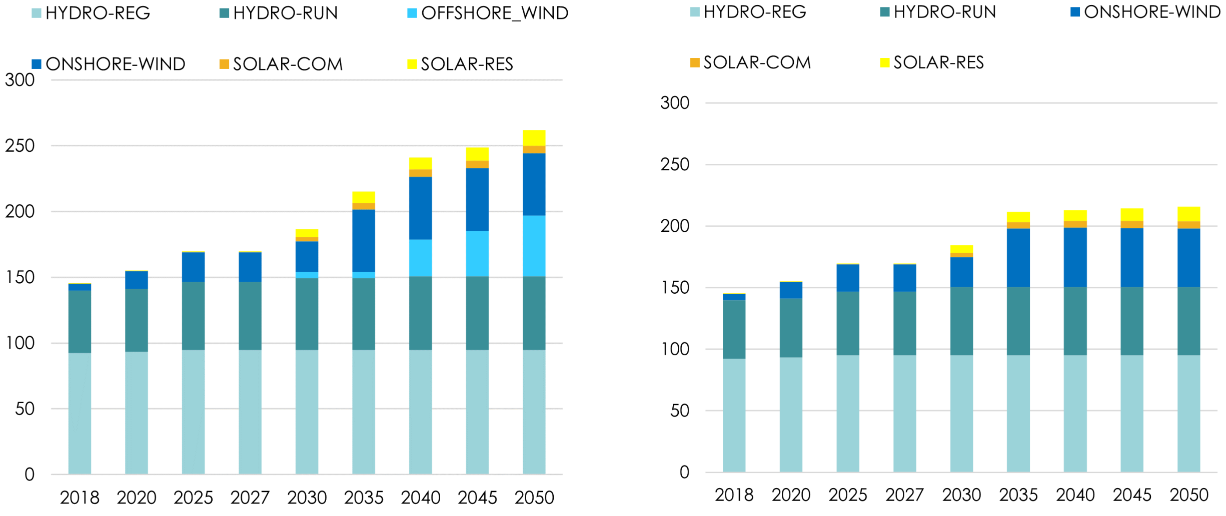
6.4 The Impact of Electrification on the Norwegian Energy System

An important factor in determining whether electrification is profitable and feasible is the impact of electrification on the Norwegian power system.

6.4.1 Total Production from Renewable Energy Sources

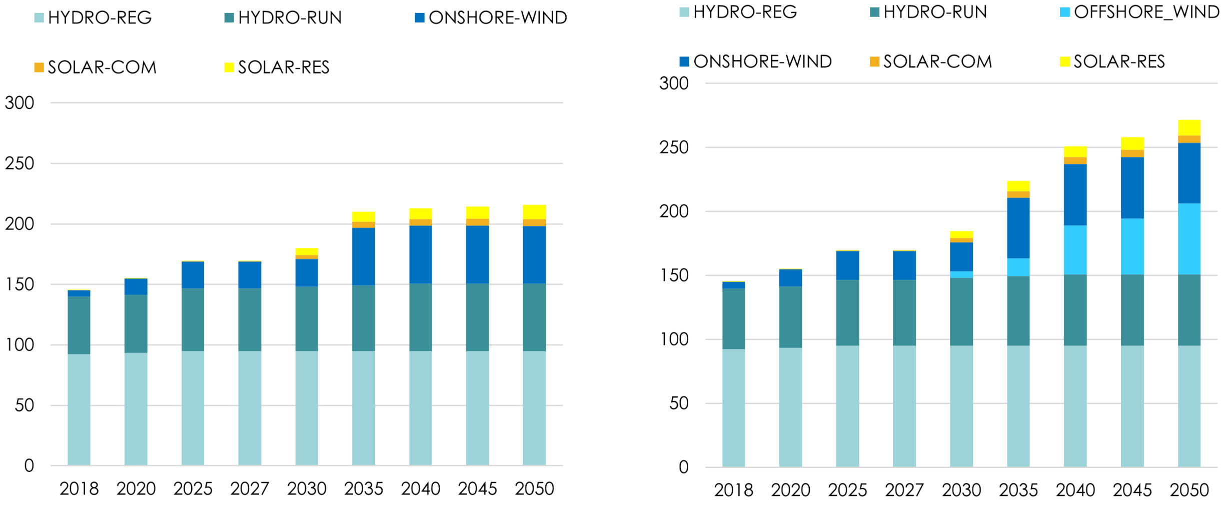
The share of renewable energy sources (RES) production during the modeling period 2018 to 2050 can be seen in Figure 6.9 for the different scenarios. It should be noted that other RES production has also been optimized by the model over the time period, however, RES investments have a maximum upper limit. The results indicate that in scenarios where offshore wind is not allowed, the model imports power from Europe instead of investing in the maximum RES capacity for solar and landbased wind. This indicates that it is more cost-effective to import power beyond what is already installed RES production and optimized by the model to fulfill Norway's total energy demand. However, the model invests in the maximum landbased wind capacity from 2035, which can be explained by wind costs decreasing from 2030.

As seen in figure 6.9b, and 6.9c, ONLYPFS and NONE scenario did not have the opportunity to electrify the O&G demand using offshore wind, hence neither invest in the offshore wind at all. Based on this, it can be seen that the total energy production of RES in Norway is lower than in the scenarios where electrification with offshore wind is allowed. Additionally, having the option to electrify with offshore wind increases the total RES production within Norway at about 50 TWh in the LIMITED and ONLYOW scenario in 2050. Of this, the majority of the offshore wind production is exported to Europe, while only 30% is used in the electrification of Norway for the ONLYOW scenario. However, increasing the RES



(a) LIMITED Scenario

(b) ONLYPFS Scenario



(c) NONE Scenario

(d) ONLYOW Scenario

Figure 6.9: RES energy production for the various scenarios, TWh/year.

production in Norway is important as the total power demand will increase along with transitioning to green energy towards 2050. Looking into the share of RES production, RES production is dominated by hydropower, which is due to a large number of existing installations. A significant investment will be made in renewable energy sources from 2035, including offshore wind, solar power, and additional onshore wind. As a result of new investments in RES, both landbased and offshore wind contribute to the largest increase in the production from RES.

6.4.2 Power Balance within Norway

A closer look at exports and imports has been conducted in order to assess how electrification from shore and offshore wind affects the Norwegian power balance. Figure 6.10 illustrates net-export (positive value) for the regions NO1-NO4 towards 2050 for the various scenarios. The results include new trade links between Europe and Norway, new trade links between offshore wind parks and the mainland, and lastly existing trade links between Norway and Europe. This overview does not include offshore wind energy exported directly abroad, as it goes directly from the offshore wind farm to Europe and does not pass through the mainland of Norway. As well, NO5 is excluded since Europe and NO5 are not connected.

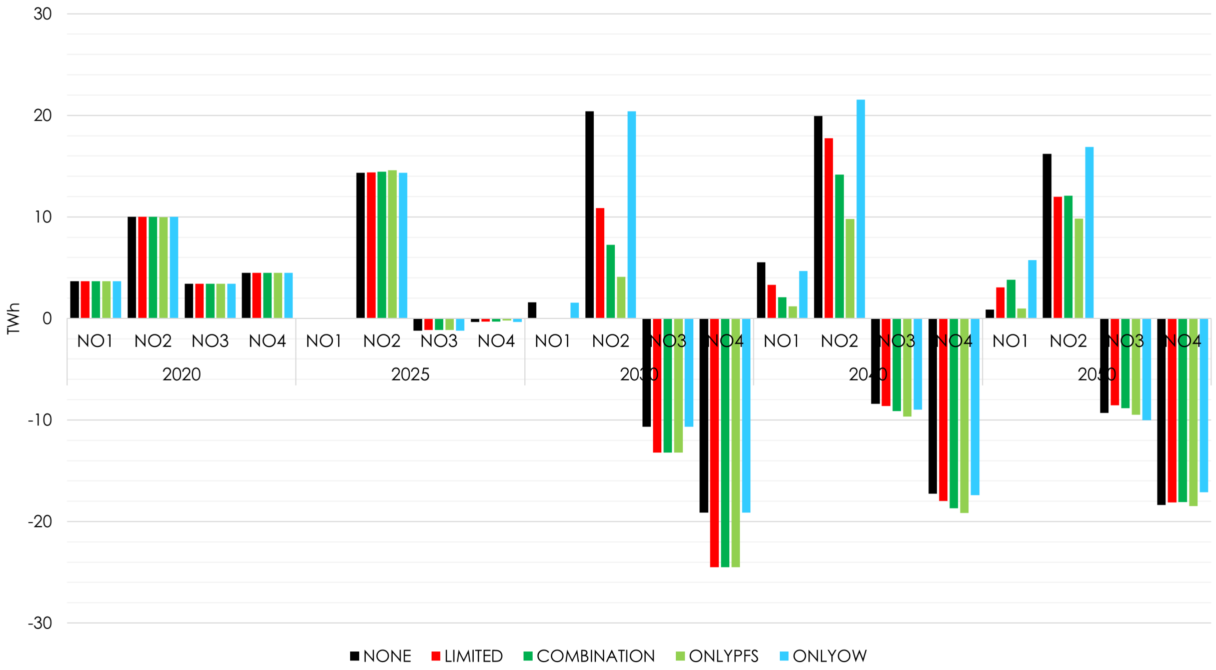


Figure 6.10: Power balance within Norway illustrating the net-export in regions NO1-NO5 for all scenarios.

Focusing on the power balance within Norway, figure 6.10 results show that:

- For 2020, Norway produces more power than it used and therefore is the net exporter for all regions in all scenarios.
- For 2025, Norway still is a net exporter but NO1, NO2, and NO3 experience the increased power demand within Norway and at the NCS.
- In 2030, the power consumption within Norway increases more than the power produced and as a result, Norway becomes a net importer and import a lot of power to regions NO3 and NO4 for all scenarios.
- From 2030, the electrification of the NCS affects the scenarios, resulting in differences between them. In comparison to no electrification, the LIMITED, COMBINATION, and ONLYPFS scenarios require 5 TWh additional import to region NO4.
- There are large differences between the various scenarios in NO2, of which ONLYPFS, COMBINATION, and LIMITED have significantly fewer exports compared to other scenarios, this is assumed to be due to the high electrification using power from shore which takes place in region NO2, resulting in an increase in power demand for that region, as also can be seen in the model electrification(ref.6.8a) for the COMBINATION scenario.
- In light of the similarities between the NONE and ONLYOW scenario, it is interesting to note that electrification of the NCS with electricity from offshore wind in 2030 has the same influence on the power balance as if it were not electrified. This may also be a result of the low share of wind capacity in 2030. While for the remaining years, this probably occurs since most of the offshore wind production is exported to Europe as this is not included in the figure.
- In 2040 and 2050, ONLYOW is the highest net exporter in NO2. This can be explained by the increased accessibility of more power due to wind power production.

Comparing NONE to ONLYPFS in 2040, one sees considerably less exports and significantly more imports, this may indicate that some of the NCS electrification is covered using power from Europe. It also looks like this when comparing RES production in the two scenarios (ref. 6.9b, 6.9c) in which it appears to be at the same level. However, it may be questionable whether Norway is entitled to use European power to electrify the O&G industry when there is a question of whether Europe will have sufficient power to power its own demands towards 2050. One could argue that the increased imports of power from Europe will result in a higher level of electrification, thereby freeing up additional gas for export back to Europe. As a result, as noted in the literature, European gas-fired power plants are more efficient than gas turbines used on the NCS, resulting in greater reductions in emissions. While at the same time, one may conclude that it might be somewhat unethical, and one may question whether the overall emission reductions are actually high enough to make the emission accounting for Europe profitable. It is also questionable whether the modeling should have limited the imports allowed to ensure only Norwegian power is used for NCS electrification. Although it is difficult to conclude which is the "most effective" solution for NCS electrification, the most important factor should be focused on achieving the highest overall emission reduction.

From these results, it can be obtained that using only offshore wind electrification has the least influence on the power balance of Norway, while ONLYPFS, LIMITED, and COMBINATION scenarios are influencing the most in terms of how much import Norway needed to the region.

6.4.3 Export Volumes to Europe

Figure 6.11 shows the net export (positive value) with Europe connections for 2030 and 2040 for all scenarios. Note that the model base assumptions such as the total demand for power are the same in all scenarios. However, the scenarios are differentiated due to the type of electrification and the electrification rate optimized by the model, resulting in various needs for electricity from landbased power or offshore wind. The growth in demand, as well as generation from other renewable sources, are also included as it is a part of the detailed energy system of TIMES.

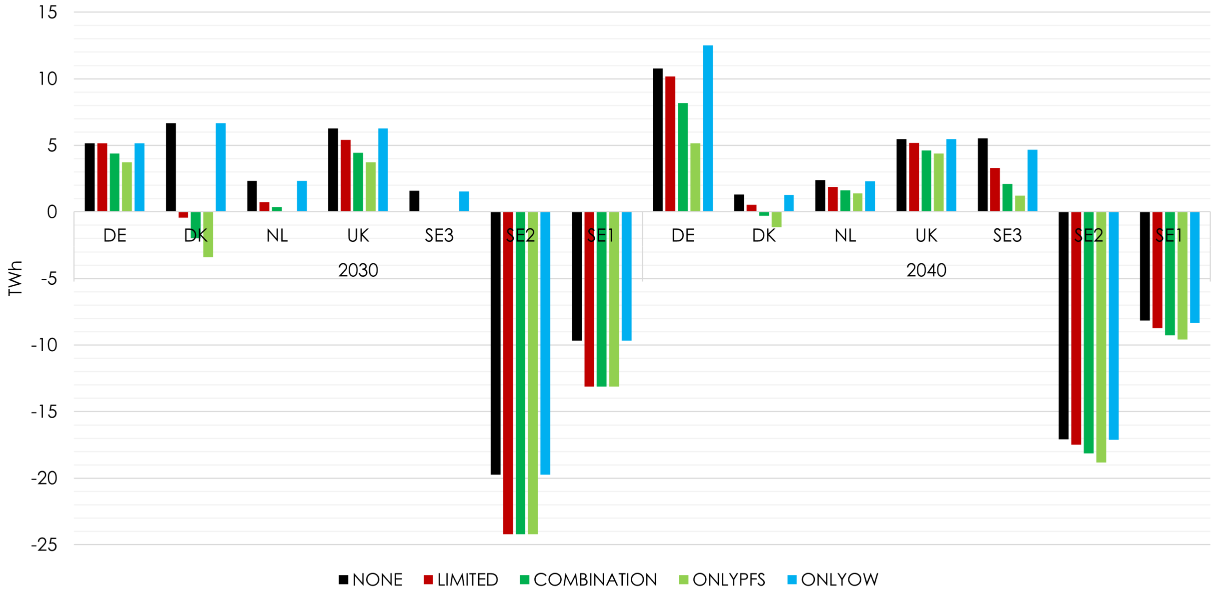


Figure 6.11: Net-export with European connections from NO in 2030 and 2040 for simulated scenarios.

Focusing on net-export interconnections to Europe in 2030 and 2040, figure 6.11 results shows that:

- Norway is net-exporter to the United Kingdom(UK) for both 2030 and 2040. This can be explained by the United Kingdom having the highest electricity prices (ref. 4.1), as a result, Norway tries to avoid importing power from the UK.
- Norway has the highest import from Sweden(SE2, SE1), which partly can be explained by the tight interconnection between Norway and Sweden, also that the power trade prices generally are lower than importing power from other countries.
- By comparing the various scenarios, it can be seen that ONLYOW is the scenario with the highest net export to Europe for almost all regions, which is not surprising given the high RES production. One can also see that ONLYPFS and COMBINATION have the highest import from Europe, which can be explained by the high demand for power partly due to the high electrification rate.

Besides this list, one can see that it is usually seen that whether offshore wind is included (ONLYOW, COMBINATION, LIMITED) or not (ONLYPFS, NONE) is what gives the most differences in the net-export with Europe connections.

6.4.4 Electricity Prices

Figure 6.12 illustrates the average hourly spot prices aggregated for all regions in 2030, and how spot prices vary under various scenarios. The prices are computed according to a supply-demand balance within the model. The results show that electrification of the NCS with power from shore will increase electricity prices on average by about 11% compared to zero electrification in 2030. This is supported by the literature review, which stated that power from shore electrification would increase electricity prices. Interestingly, the electricity prices in the scenario using only offshore wind (ONLYOW) are almost the same as in the scenario with no electrification (NONE). One explanation may be that offshore wind electrification will take place more gradually as the amount of electrification allowed is limited according to government plans, also the little investment in offshore wind in 2030. While the other scenarios show that the price difference is greater compared to the no electrification scenario. One factor that may contribute to this is the fact that electrification occurs much earlier

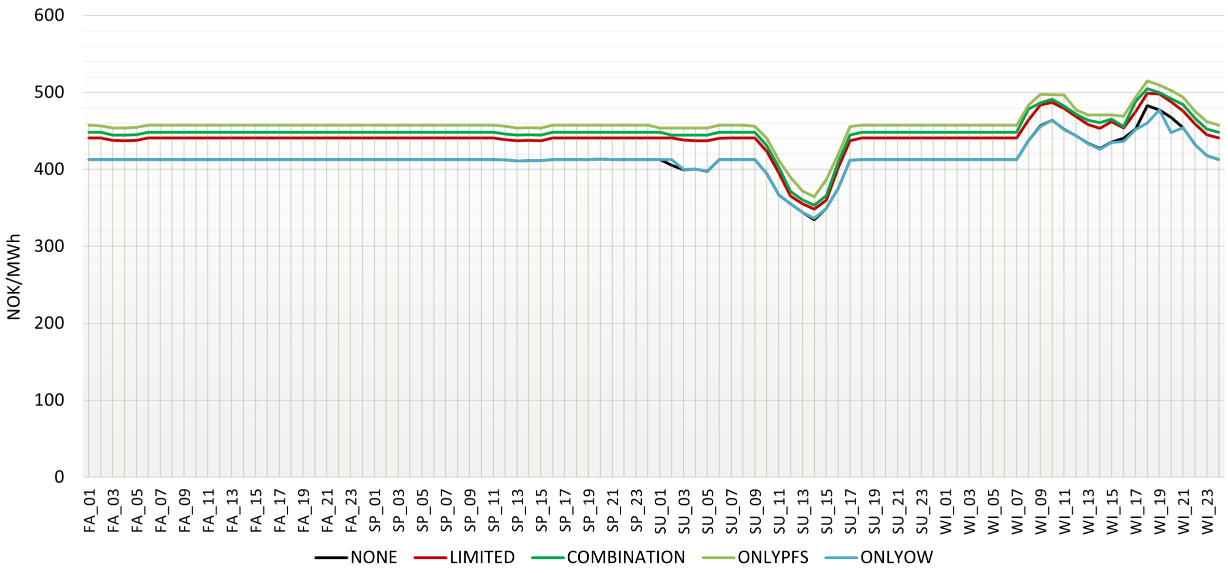


Figure 6.12: Average hourly spot prices aggregated for all regions in 2030 for all five scenarios, NOK/MWh.

than the power grid is prepared for, as well as a substantial increase in electricity demand in 2030 as a result of large investments in power from shore. By 2050 the price difference for electricity has evened out, which may be due to both the fact that by 2050 an extensive amount of electrification has already been implemented, as well as the fact that demand for electricity in the petroleum industry has decreased, which has evened out the significant price differences between the various scenarios. According to the model results, there were also price differences for the different regions, with NO2 being the most expensive region for all scenarios. This can be explained by the fact that NO2 is the region with the most international cables, which means that a considerable amount of power is exported through NO2 and this, in turn, makes domestic power more expensive. Nonetheless, model results of regional prices are not included, since there is no significant difference between the various scenarios.

Summer is a time when Norwegian power demand is at its lowest due to higher temperatures, explaining the dip in the figure. As with summer, there is a peak in winter as a result of cold winter days, which in turn leads to a higher amount of energy consumed and lower energy produced from solar energy.

6.5 The Overall Effect of Electrifying the NCS

Electrification at the rapid pace proposed in COMBINATION, LIMITED, and ONLYPFS, will result in an increased electricity demand of 30.6, 26.6, or 31.6 TWh. This equals approximately 20 % of the total RES power production of 146 TWh in 2022 [52] in Norway. The high level of electrification will require major investments and the development of new power from shore cables. Despite this, model results show that new cables between the regions(NO1-NO5) will not be needed as a result of NCS electrification, but note that the model does not include the regional- and distribution grid. Whereas, there is likely that investments here would be necessary to accomplish the electrification proposed. For all scenarios, new cables to Europe (NO1-SE, NO2-SE2, NO4-SE1) will be required from 2030. This is probably due to the increased demand for power towards 2050, even without electrification. Furthermore, for all scenarios involving offshore wind, new investments are made in transmission cables from NO2 to Germany. This can be explained by the fact that increased power production provides room for sending more power to Europe. With the shift to renewable energy, more energy-intensive sectors such as industry, transportation, and petroleum will need new power cables and asses to sufficient power for electrification, resulting in increased competition to connect to the grid. This means that, in reality, electrification projects on the shelf may be postponed if they are not prioritized. Based on this offshore wind production may be advantageous as it contributes to increased RES production of as much as 50 TWh in 2050.

In the ONLYOW scenario, there is a clear difference between what is the realistic development of offshore wind based on current assumptions (model simulation) VS the optimistic large development of offshore wind towards 2050 (30 GW) that the government proposes. The scenario, on the other hand, shows that significantly more incentives are required on the part of the government if it is to be realistic to achieve the high offshore wind capacity that they are aiming for. The ONLYOW scenario illustrates that offshore wind can contribute with more power to the grid and help balance the power on land from 2040, therefore not be as much burden on the power grid as only electrifying with power from shore. Offshore wind could also lead to increased revenues from exports abroad. In other words, there are several advantages to offshore wind, but based on current assumptions, the proportion of offshore wind invested is much smaller than the government has planned.

The effect of electrification on the energy system will also be affected by the level of production activity on the Norwegian continental shelf and the extent to which industrial development will take place on land towards 2050. In this regard, it would be very interesting to investigate later how the model results would be affected by a very high or very low production level on the Norwegian shelf. Additionally, consider the effects of different levels of industrial development on land. Unfortunately, there was not enough time in this project to investigate these aspects.

Chapter 7

Conclusions and Further Research

This study has focused on exploring different decarbonization pathways for the Norwegian continental shelf using offshore wind and power from shore. The already existing IFE-TIMES-Norway optimization model has been further developed to include offshore regions and power cables between onshore and offshore regions. As a result, IFE-TIMES-Norway was able to be used as a simulation tool during this master thesis to evaluate the feasibility of electrifying the Norwegian continental shelf under various long-term future energy scenarios.

7.1 Conclusions

In response to the research questions, simulated scenarios led to the following conclusions:

RQ1: What are the potential for CO_2-emission reductions by electrifying the platforms with offshore wind energy and/or power from shore?

Using only power from shore or a combination between offshore wind and shore power showed the greatest emission reduction beyond 55% compared to 1990 values by 2030 (equals to 75% reduction from 2018 to 2030). While, offshore wind power alone resulted in a 25% emission reduction from 2018 to 2030, which is equal to emissions that are 15% higher than of 1990 values. All scenarios besides NONE showed net-zero emissions by the latest 2050, which all are a result of increased electrification and decommissioned fields.

RQ2: How do the offshore wind resources differ across the Norwegian Continental shelf and how do they match the demand of offshore O&G platforms?

Generally, the optimized offshore wind production sites are evenly distributed across the southwest and west coast, while the remainder of the shelf are having scarcer wind resources allocated based on model investments. Looking at how offshore wind matches O&G demand, it can be seen that in both 2030 and 2035, the required gas consumption that needs to be electrified to follow the emission pathway suggested by [52] is not met. There are several reasons that this demand is not met. Firstly, there is insufficient offshore wind production planned by the government by 2030 to meet the government's climate target of a 55% reduction in emissions by 2030 on the NCS. In order to meet this target through offshore wind production, the government should allow for a total wind capacity of at least 6 GW, which is currently at 3 GW. Secondly, the model does not utilize the full offshore wind capacity planned by the government which can be explained by the fact that TIMES is an optimization model with the objective of minimizing the total discounted system cost, where offshore wind is currently not competitive enough to meet the energy demand of O&G fields of that in 2030, paying CO_2 taxes is a more cost-effective option. However, offshore wind has the potential to meet NCS energy demands between 2040 and 2050, considering both the decline in O&G consumption and the increased electrification.

The main limitation is that the time resolution used for modeling offshore wind resources gives model results that do not take into consideration the hourly demand for gas turbines during periods of low offshore wind energy production. Consequently, it is not clear what effects wind conditions at various wind parks have on the need for backup turbines. In spite of this limitation, the model is able to provide valuable insight into the most suitable offshore regions for electrification, and how much of the total NCS energy demand can be met by offshore wind.

RQ3: What are the most cost-efficient solutions for decarbonizing the oil and gas industry in Norway?

Using both offshore wind and power from shore (COMBINATION) was found to be the most cost-effective way of decarbonizing the oil and gas industry as it resulted in the lowest total discounted system cost. The second most cost-efficient solution was using only power from shore (ONLYPFS), whereas some of the NCS electrification is covered using power from Europe. Interestingly, when comparing LIMITED with COMBINATION and ONLYPFS, it turns out to be the most cost-effective to electrify the oil and gas industry at a faster rate than needed to reach 2030 and 2050 climate targets.

RQ4: How is the Norwegian energy system impacted by electrification and large-scale offshore wind production (e.g., electricity prices, export volumes, and land-based RES production)?

Results of the various scenarios show that electrification of the shelf will have a greater impact on the Norwegian power system than without electrification. It is also found that electrification through offshore wind has the least negative impact on the power system compared to other electrification options. As a result of large-scale offshore wind production, the total RES production within Norway will increase by approximately 50 TWh in 2050, which contributes to supplying O&G demand, land (NO1-NO5), and Europe with electricity. In addition, this electrification is more gradual than the development seen for LIMITED, COMBINATION, and ONLYPFS. As a result of the increased need for power in Norway due to both electrification of the NCS and digitization, it is seen in 2030 that Norway is no longer a net exporter. The results illustrate that electrification of the NCS with power from shore will result in higher electricity prices on average by about 11% compared to zero electrification in 2030. To implement electrification at the pace proposed in COMBINATION, LIMITED, and ONLYPFS require an increased electricity demand of 30.6, 26.6, or 31.6 TWh, this corresponds to approximately 20% of the total power production of 146 TWh in 2022[54] in Norway. By 2050 the price difference for electricity has evened out, which may be due to both the fact that by 2050 an extensive amount of electrification has already been implemented, as well as the fact that demand for electricity in the petroleum industry has decreased, which has evened out the significant price differences between the various scenarios.

Overall, the simulated scenarios demonstrated a successful implementation of offshore regions. The simulations proved to be a valuable tool for exploring different electrification futures on the NCS, and a valuable tool to evaluate how the Norwegian power system are impacted by electrification. A main advantage of the model is its capability to take into account several factors such as costs, emissions, demand and flow of energy. Based on all this, the results can give valuable insight into which O&G fields should be electrified and how. On the other hand, the main disadvantage of the model is its disability to provide results of which hours there are needed for backup turbines during low wind production.

7.2 Further Research

The findings of this master's thesis suggest that further research in the area is proposed to explore additional aspects and include more components to IFE-TIMES-Norway in terms of exploring NCS electrification. The following recommendations are outlined for further research and development of IFE-TIMES-Norway in relation to the electrification of the NCS.

- When assessing electrification of the NCS using offshore wind, future studies should consider implementing a time resolution of offshore wind resources that will allow backup gas turbines to be accounted for. This will allow us to fully understand how offshore wind match O&G demand, the challenges and limitations of transitioning to a fully electrified O&G installation, including the role of backup gas turbines.
- Study how the fluctuations in wind in shorter periods affect the use of offshore wind electrification.
- Update and include offshore wind areas within IFE-TIMES-Norway as a basis for the new NVE report that will be published in April 2023.
- Enhance the model to include electrification options in addition to offshore wind and shore power (e.g., hydrogen production, ammonia production, CCS).
- Future electrification scenarios should take into account the impacts of different levels of industrial development on the energy system and the production activity of the O&G industry on the NCS.
- Studying how queueing systems work and developing a methodological approach for implementing this into IFE-TIMES-Norway.
- Investigate the increased gas export to Europe as a result of electrification (e.g., income, availability infrastructure).
- Conduct a sensitivity analysis in TIMES.

References

[1] Capgemini and Energy Valley, "Creating offshore winners, how norway can become a global leader in offshore wind," Oslo, Norway, Aug. 2022.

[2] Det Norske Veritas, "Energy transition norway 2022 - a national forecast to 2050," DNV, Høvik, Norway, 2022.

[3] The Norwegian Petroleum Directorate, "Det investeres for framtiden på sokkelen," NPD, Jan. 2023, Assessed: 25.02.2023. [Online]. Available: `https://www.npd.no/fakta/nyheter/generelle-nyheter/2023/det-investeres-for-framtiden-pa-sokkelen/`.

[4] The Norwegian Petroleum Directorate, The Norwegian Water Resources and Energy Directorate, and The Environmental Agency, "Kraft fra land til norsk sokkel," NPD, Stavanger, Norway, 2020.

[5] E.A.Mathiesen, "Integrating offshore wind in the electrification of the norwegian continental shelf," ENE 503 Energy Research Project, Unpublished, Grimstad, Norway, Nov. 22.

[6] D. Grainger, A. U. Bindingsbø, O. Brekke, G. De Koeijer, O. Rekaa Nilssen, and J. Pettersen, "Reducing co_2 emissions from offshore oil and gas production," *SSRN Electronic Journal*, Feb. 2021. [Online]. Available: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3820726`.

[7] I. Marie Solbrekke, N. Gunnar Kvamstø, and A. Sorteberg, "Mitigation of offshore wind power intermittency by interconnection of production sites," *Wind Energy Science*, vol. 5, no. 4, pp. 1663–1678, Nov. 2020, ISSN: 23667451. DOI: `10.5194/WES-5-1663-2020`.

[8] Federation of Norwegian Industries (NI), Norwegian Shipowners Association (LO), Confederation of Norwegian Enterprise (NHO), and Norwegian Confederation of Trade Unions (LO), "The energy industry of tomorrow on the continental shelf climate strategy towards 2030 and 2050 status report 2022," Konkraft, Norway, 2022.

[9] The Norwegian Environment Agency, "Grønn omstilling: Klimatiltaksanalyse for petroleum, industri og energiforsyning," EA, Trondheim, Norway, M-2346, Sep. 2022.

[10] M. Gravdal, "Offshore electrification - an overview of technologies, risks and costs associated to the norwegian continental shelf," M. S. thesis, Department of Science and Technology, Stavanger, Norway, 2022.

[11] S. Roussanaly, A. Aasen, R. Anantharaman, *et al.*, "Offshore power generation with carbon capture and storage to decarbonise mainland electricity and offshore oil and gas installations: A techno-economic analysis," *Applied Energy*, vol. 233-234, pp. 478–494, Jan. 2019, ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2018.10.020`.

[12] J. I. Marvik, E. V. Øyslebø, and M. Korpås, "Electrification of offshore petroleum installations with offshore wind integration," *Renewable Energy*, vol. 50, pp. 558–564, Feb. 2013, ISSN: 0960-1481. DOI: `10.1016/J.RENENE.2012.07.010`.

[13] L. Reichenberg, A. Wojciechowski, F. Hedenus, and F. Johnsson, *Geographic aggregation of wind power—an optimization methodology for avoiding low outputs*. John Wiley & Sons, Ltd, Jan. 2017, vol. 20, pp. 19–32. DOI: `10.1002/WE.1987`.

[14] European Commission (EU), "Communication from the commission to the European Parliament, the European Council, the council, the European economic and social committee and the committee of the regions," *REPowerEU Plan*, no. 52022DC0230, May 2022.

[15] International Energy Agency (IEA), "Net zero by 2050 - a roadmap for the global energy sector," IEA, Paris, 2021, License: CC BY 4.0. [Online]. Available: `https://www.iea.org/reports/net-zero-by-2050`.

[16] World Wide Fund, "Norge ut av oljealderen," WWF, Accessed: 13.02.2023. [Online]. Available: `https://www.wwf.no/klima-og-energi/ut-av-oljealderen`.

[17] The Norwegian Petroleum Directorate, *Tfo 2022: 25 selskaper får tilbud om andeler*, Accessed: 15.02.2023, Jan. 2023. [Online]. Available: `https://www.npd.no/fakta/nyheter/generelle-nyheter/2023/tfo-2022-25-selskaper-far-tilbud-om-andeler/`.

[18] Government of Norway, "Hurdalsplattformen for en regjering utgått fra arbeiderpartiet og senterpartiet 2021-2025," Oslo, Norway, Oct. 2021. [Online]. Available: `https://www.regjeringen.no/no/dokumenter/hurdalsplattformen/id2877252/`.

[19] Norwegian Petroleum Directorate, "Resource report 2022," Stavanger, Norway, 2022. [Online]. Available: `https://www.npd.no/globalassets/1-npd/publikasjoner/rapporter/ressursrapporter/2022/en/resource-report-2022.pdf`.

[20] The Norwegian Petroleum Directorate, *Production forecasts*, Jan. 2023. [Online]. Available: `https://www.norskpetroleum.no/en/production-and-exports/production-forecasts/`.

[21] "Contribution of the basilicata region to decarbonisation of the energy system: Results of a scenario analysis," *Renewable and Sustainable Energy Reviews*, vol. 138, p. 110 544, 2021, ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2020.110544`.

[22] S. Bhattacharyya and G. Timilsina, "A review of energy system models," *International Journal of Energy Sector Management*, vol. 4, pp. 494–518, Nov. 2010. DOI: `10.1108/17506221011092742`.

[23] S.C.Bhattacharyya and G.Timilsina, "A review of energy system models," *International Journal of Energy Sector Management*, vol. 4, no. 4, pp. 494–518, 2010. [Online]. Available: `https://doi.org/10.1108/17506221011092742`.

[24] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, "Classification and challenges of bottom-up energy system models - a review," *Renewable and Sustainable Energy Reviews*, vol. 129, p. 109 917, 2020, ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2020.109917`.

[25] S. Hilpert, C. Kaldemeyer, U. Krien, S. Günther, C. Wingenbach, and G. Plessmann, "The open energy modelling framework (oemof) - a new approach to facilitate open science in energy system modelling," *Energy Strategy Reviews*, vol. 22, pp. 16–25, 2018, ISSN: 2211-467X. DOI: `https://doi.org/10.1016/j.esr.2018.07.001`.

[26] M. Borasio and S. Moret, "Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the italian energy transition," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111 730, 2022, ISSN: 1364-0321. DOI: `https://doi.org/10.1016/j.rser.2021.111730`.

[27] "The energy supply model message," IIASA, Laxenburg, Austria, IIASA Research Report, Dec. 1981. [Online]. Available: `https://pure.iiasa.ac.at/id/eprint/1542/`.

[28] P. Sullivan, V. Krey, and K. Riahi, "Impacts of considering electric sector variability and reliability in the message model," *Energy Strategy Reviews*, vol. 1, no. 3, pp. 157–163, 2013, Future Energy Systems and Market Integration of Wind Power, ISSN: 2211-467X. DOI: `https://doi.org/10.1016/j.esr.2013.01.001`.

[29] F. Wiese, R. Bramstoft, H. Koduvere, *et al.*, "Balmorel open source energy system model," *Energy Strategy Reviews*, vol. 20, pp. 26–34, 2018, ISSN: 2211-467X. DOI: `https://doi.org/10.1016/j.esr.2018.01.003`.

[30] R.Loulou, G.Goldstein, A.Kanudia, A.Lettila, and U.Remme, "Documentation for the times model part 1," iea-ETSAP, 2021. [Online]. Available: `https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I.pdf`.

[31] K. Espegren, S. Damman, P. Pisciella, I. Graabak, and A. Tomasgard, "The role of hydrogen in the transition from a petroleum economy to a low-carbon society," *International Journal of Hydrogen Energy*, vol. 46, no. 45, pp. 23 125–23 138, 2021, Hydrogen Separation, Production and Storage, ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2021.04.143.

[32] P. Seljom, E. Rosenberg, L. E. Schäffer, and M. Fodstad, "Bidirectional linkage between a long-term energy system and a short-term power market model," *Energy*, vol. 198, p. 117 311, 2020, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2020.117311.

[33] P. Seljom, L. Kvalbein, L. Hellemo, M. Kaut, and M. M. Ortiz, "Stochastic modelling of variable renewables in long-term energy models: Dataset, scenario generation quality of results," *Energy*, vol. 236, p. 121 415, 2021, ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2021.121415.

[34] E. Rosenberg, K.Espegren, J.Danebergs, *et al.*, "Modelling the interaction between the energy system and road freight," Mar. 2022. DOI: http://dx.doi.org/10.2139/ssrn.4066994.

[35] K.Haaskjold, E.Rosenberg, and P.M.Seljom, "Documentation of ife-times-norway v3," no. IFE/E-2022/013, p. 86, Feb. 2023, ISSN: 2535-6380.

[36] K. Karlsson, M. Gargiulo, V. Verda, and R. Gerbonia, "Modeling of the norwegian power system and analysis of the power trade in the nordic countries," M. S. thesis, Danish Technical University (DTU), Mar. 2015.

[37] A.Lind, E.Rosenberg, and K.Espegren, "Times-norway model documentation," no. IFE/KR/E-2013/001, Dec. 2013, ISSN: 0333-2039.

[38] The Norwegian Petroleum Directorate, *Felt på norsk sokkel*, Assessed: 05.02.2023. [Online]. Available: https://www.norskpetroleum.no/fakta/felt/.

[39] A.Nybø, M.Winsnes, and A.Ljønes, "Tilknytning av nye havvindområder til land," Statnett, Oslo, Norway, Feb. 2023.

[40] Institute for Energy Technology (IFE), "Cost data for offshore wind development, including total investment costs and grid investment costs," Unpublished, Jan. 2023.

[41] W.T.Hsu, "Monopile, jacket or floater, how do i pick the right option for my offshore wind project?," Jan. 2020, Assessed: 10.02.2023. [Online]. Available: https://www.empireengineering.co.uk/monopile-jacket-or-floater-how-do-i-pick-the-right-option-for-my-offshore-wind-project/.

[42] International Renewable Energy Agency, "Innovation outlook: Offshore wind," 2016, IRENA, Abu Dhabi.

[43] ABB, "Electrification of petroleum installations commercial justifiable and necessary for the climate," Assessed: 01.02.2023, ABB.com. [Online]. Available: https://new.abb.com/docs/librariesprovider50/om-oss---barekraftig-utvikling/electrification-of-petroleum-installations-highresolution.pdf.

[44] K. S. Berg, M. Carlsen, T. Eirum, *et al.*, "Havvind, strategisk konsekvensutredning," no. 47-12, Dec. 2012, Oslo, Norway. [Online]. Available: https://publikasjoner.nve.no/rapport/2012/rapport2012_47.pdf.

[45] M.I.Tahir, "Derfor elektrifiserer vi norsk sokkel," Mar. 2022. [Online]. Available: https://offshorenorge.no/om-oss/nyheter/2021/12/derfor-elektrifiserer-vi-norsk-sokkel/.

[46] Norwegian Environmental Agency, *Oversikt virksomheter*, Assessed: 05.01.2023. [Online]. Available: https://www.norskeutslipp.no/no/Listesider/Virksomheter/?SectorID=700.

[47] Equinor, "Data of power from shore demand," Unpublished, Feb. 2023.

[48] Government of Norway, *Perspektivmeldingen 2021, meld. st. 14*, Regjeringen.no, 2021. [Online]. Available: https://www.regjeringen.no/no/dokumenter/meld.-st.-14-20202021/id2834218/.

[49] Statistics Norway, *11561: Energibalansen. tilgang og forbruk, etter energiprodukt, statistikkvariabel, år og energibalanseposter*, Accessed: 02.02.2023. [Online]. Available: `https://www.ssb.no/statbank/table/11561/tableViewLayout1/`.

[50] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, 2016, ISSN: 0360-5442. DOI: `https://doi.org/10.1016/j.energy.2016.08.068`.

[51] S.Pfenninger and I.Staffell, "Renewable.ninja," license: CC BY-NC 4.0, Assessed: 15.01.2023. [Online]. Available: `https://www.renewables.ninja/`.

[52] Norsk klimastiftelse, "Olje og gass," 2023, Assessed: 17.03.2023. [Online]. Available: `https://www.tilnull.no/klimagassutslipp/OIL_AND_GAS`.

[53] Government of Norway, *Meld. st. 36 (2020–2021) energi til arbeid – langsiktig verdiskaping fra norske energiressurser*, Regjeringen.no, 2021. [Online]. Available: `https://www.regjeringen.no/no/dokumenter/meld.-st.-36-20202021/id2860081/?ch=5`.

[54] H.Tonne, "2022 – nok et eksepsjonelt kraftår," Jan. 2023, Statnett.no. [Online]. Available: `https://www.statnett.no/om-statnett/nyheter-og-pressemeldinger/nyhetsarkiv-2023/2022--nok-et-eksepsjonelt-kraftar/`.

Appendix A

Overview of included O&G fields

Table A.1: List of the O&G fields included in the modeling along with the associated group in TIMES, the planned decommissioning year, and the production start year [5] [9] [46].

O&G Field	Group in TIMES	Planned Decom.	Prod.start
AAsta Hansteen	G4	2031	2018
Alvheim	G17	2040	2008
Balder	G10	2030	2018
Brage	G9	2030	1993
Draugen	G6	2040	1993
Edvard Grieg	G11	2035	2015
Ekofisk	G15	2050	1971
Eldfisk	G15	2050	1979
Gina Krog	G12	2032	2017
Gjøa	G8	2040	2010
Goliat	G2	2035	2016
Grane	G10	2044	2003
Gudrun	G11	2032	2014
Gullfaks	G7	2035	1986
Heimdal	G13	2024	1985
Johan Sverdrup	G11	2059	2019
Kristin	G5	2034	2005
Kvitebjørn	G7	2045	2004
Martin Linge	G9	2044	2021
Melkøya facility(Snøhvit)	G3	2050	2007
Njord	G6	2040	1997
Norne	G3	2036	1997
Nyhamna facility(Ormen Lange)	G6	2042	2007
Oseberg	G9	2040	1988
Oseberg sør	G9	2039	2000
Oseberg øst	G9	2027	1999
Skarv	G3	2039	2013
Sleipner	G12	2032	1993
Snorre	G7	2040	1992
Statfjord	G7	2027(A)/2035(B and C)	1979
Troll	G9	2066(A)/ 2040(B and C)	1995
Ula	G14	2028	1986
Valhall	G15	2049	1982
Veslefrikk	G9	2022	1989
Visund	G7	2034	1999
Yme	G16	2031	2021
Åsgard	G5	2032	1999
Heidrun	G5	2044	1995
Johan Castberg	G1	2054	2024