Master's thesis

NTNU
Norwegian University of Science and Technology
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Dynamic process modelling of topside systems to evaluate power consumption and coupling with periodic power supply from renewables

Master's thesis in Petroleum Geoscience and Engineering
Supervisor: Milan Stanko
June 2022

NTNU
Kunnskap for en bedre verden

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Abstract

Over the past decade, there has been a change in the Norwegian oil and gas production sector to reduce its overall carbon emissions by focusing its efforts on greener, more environmental-friendly methods of oil and gas extraction. This is, in large part, due to the Norwegian government's regulations to reduce the country's carbon footprint in order to achieve zero emissions from oil and gas operations on the Norwegian Continental Shelf by 2050. Significant portions of Norway's overall carbon emissions are attributed to the oil and gas industry. Therefore, in order to achieve the necessary reductions in carbon emissions, the industry must evaluate various methods of reducing carbon emissions from the production of oil and gas.

This thesis aims to evaluate the potential of wind power as a substitute to traditional gas turbines for supplying power to offshore production facilities, specifically the oil and gas processing plants at these offshore facilities. In order to perform this evaluation, the thesis first presents a dynamic, simulated process model built using the software K-Spice. A three separation stage process system is built for the separation of oil, gas and water. The model's adaptability to varying production demands is then tested to determine its operational limits. Lastly, the model's power consumption, under these varying production rates, is noted by combining the power consumption of each component that is fueled by electrical power, such as the compressors and the oil pump. Next, wind data gathered at Gullfaks E126, which is a section of the greater Gullfaks field, is used to determine the power generation capabilites of an offshore wind farm located at Gullfaks E126. The power consumption of the process model is then mapped along with the power generated from wind to determine whether or not there is sufficient power available to operate the process system. Finally, an analysis of the production rates of the process system, under varying power consumption levels, is conducted.

The results show that the process model is able to operate normally, i.e. without any malfunctions, when the total production rate ranges from a minimum of 50% to a maximum of 120% of the default design rate of the process model. The total power consumption of the model, based on these production rates, ranges from a minimum of 6.37MW to a maximum of 33.06 MW. The mapping of the power consumption with the power generated by wind shows that there is indeed more than sufficient power available to operate the process system. However, due to the varying nature of wind power, the power consumption of the process model has to vary accordingly. This, in turn, affects the production output of the process model as production has to either increase or decrease in order to vary the power consumption. Thus the production output of the process model does not remain stable at a specific level throughout the time period analyzed in this thesis. However, with the use of an oil storage tank, the effects of unstable production rates can be mitigated to achieve a more stable production output in the long-term. Based on the findings obtained from analyzing the available power and the power consumption, as well as the potential production capacity, wind power can indeed, at least partly, be a substitute for gas turbines as the source of power for offshore processing facilities.

Sammendrag

I løpet av det siste tiåret har det vært en endring i den norske olje- og gassindustrien for å redusere klimagassutslipp ved å satse mer på grønne og miljøvennlige metoder for olje- og gassutvinning. Dette skyldes i stor grad den norske regjeringens innsats for å redusere landets utslipp for å kunne bli et mer miljøvennlig og et null utslippsland innen 2050. Store deler av Norges samlede klimagassutlipp skyldes olje- og gassutvinnig. Derfor må industrien vurdere ulike metoder for å redusere klimagassutslipp fra olje- og gassutvinning.

Denne masteroppgaven har som mål å vurdere om havvind kan potensielt erstatte tradisjonelle gassturbiner som energikilde for olje- og gassplattformer. Fokuset er rettet spesifikt mot prosessanlegg ved plattformene. For å kunne utføre denne vurderingen, en dynamisk modell av et prosessanlegg ble bygget ved bruk av programvaren K-Spice. Prosessanlegget består av tre separator for å kunne separere olje, gass og vann fra råoljen. Modellens tilpasningsevne til varierende produksjonskrav ble testet først for å bestemme dens operasjonelle grenser. Deretter noteres modellens strømforbruk, under disse varierende produksjonskrav, ved å legge sammen strømforbruket til hver komponent som bruker strøm, som for eksempel kompressorer og oljepumpe. Deretter brukes vinddata samlet ved Gullfaks E126, som er en del av det større Gullfaks-feltet, for å bestemme kraftproduksjonsevnen til en potensiell havvindpark ved Gullfaks E126. Strømforbruket til prosessmodellen blir deretter kartlagt sammen med strøm generert av havvind for å kunne avgjøre om det er tilstrekkelig med strøm for prosessanlegget. Til slutt gjennomføres en analyse av produksjonsratene til prosessanlegget når strømforbruket til anlegget varieres.

Resultatene viser at prosessmodellen er i stand til å fungere normalt når den totale produksjonsraten varierer fra minimum 50% til maksimalt 120% av den opprinnelige produskjonsraten for prosessmodellen. Det totale strømforbruket til modellen, basert på disse produksjonsratene, varierer fra minimum 6,37 MW til maksimalt 33,06 MW. Kartleggingen av strømforbruket med strøm generert av havvind viser at det faktisk er mer enn nok strøm tilgjengelig for å kunne drive prosessanlegget. På grunn av vindkraftens varierende natur, må strømforbruket til prosessmodellen også varieres. Dette påvirker da produksjonsraten til prosessanlegget ettersom produksjonen må enten økes eller reduseres for å variere strømforbruket. Produksjonen til prosessmodellen forblir ikke dermed stabilt på et spesifikt nivå gjennom hele tidsperioden analysert i denne masteroppgaven. Gjennom bruk av en oljelagringstank kan effekten av ustabile produksjonsrater reduseres for å oppnå en mer stabil produksjonrate på lang sikt. Basert på funnene fra analyse av tilgjengelig strøm og strømforbruk, samt potensiell produksjonskapasitet, kan havvind faktisk være en erstatning for gassturbiner som energikilde for norske olje- og gassplattformer.

Acknowledgment

This thesis and the work shown in it would not have been possible to complete without the tremendous help I received from some very important people. These people have been instrumental in helping me throughout my final year at NTNU.

So with that in mind, the first person I would like to extend my gratitude to is my supervisor Professor Milan Stanko. He has been there to guide me throughout this last year. His help with not only this thesis, but all the work I have had to do this past year has been incredibly insightful. Without his guidance, this past year would have been significantly more stressful than what it was.

I would like to thank Heiner Schümann for his invaluable guidance throughout this whole process. Without him, his ideas and his creative solutions, I would not have known where to even begin. He has helped me through every issue I have faced, especially with the modelling, and without his help, I would probably still be struggling to make my model work properly. I am truly grateful for the time he has invested in this project.

I would also like to thank Leila Eyni for her help all throughout the year. She has always been there to offer her help with every task I have had to complete. She has helped me with every piece of work that has gone into creating this thesis. From solving modelling issues together to writing Python codes, her help was something I relied on heavily. I cannot thank her enough for the time she has spent helping me this past year.

Lastly, I would be remiss if I did not mention my incredible family. They have been my inspiration and have supported me throughout my journey at NTNU. I would not have achieved anything these past few years without them in my corner. They have been my light at the end of the tunnel for as long as I can remember. Everything I have accomplished, and everything I will accomplish, I owe all of it to them.

Contents

List of Figures

List of Tables

1 Introduction

1.1 The global energy sector

The energy sector across the world is undergoing a major shift towards renewable energy. Increasing pressure from governments, and the general population, towards the energy sector to reduce carbon emissions has led energy companies to refocus their efforts on renewable solutions. This pressure, along with international undertakings such as the Paris Agreement, has begun to shape a large transformation of the worldwide energy sector.

The oil and gas industry is one of the major energy producers across the world. In 2020, produced energy from oil and gas contributed to 57% of all global energy production [1]. The global population's dependence on fossil fuel energy is undeniable, and, by 2030, roughly 63 to 78% of the primary energy demand of the world is expected to be supplied by fossil fuels [2]. The extraction of oil and gas, therefore, remains important to global energy. However, the extraction of oil and gas accounts for roughly 3.6% of global greenhouse gas emissions [3]. As dependency on fossil fuel energy increases steadily, measures need to be taken to reduce carbon emissions from the overall process of energy production from fossil fuels.

In 2018, onshore production of oil and gas accounted for 72% of global production, while the remaining 28% was produced by offshore oil and gas installations [4]. Norway is one of the countries engaged in offshore oil and gas production. The country's production of oil and gas covers roughly 2% and 3%, respectively, of the global demand [5]. While the production numbers may seem relatively small compared to the global production of oil and gas, a method to achieve significant reductions in carbon emissions from Norwegian offshore oil and gas installations might prove to be an effective model for other oil and gas producing nations to implement.

1.2 Scope

The aim of this thesis is to evaluate a possible method to reduce overall carbon emissions from Norwegian offshore oil and gas installations. This evaluation will be carried out by first analyzing the petroleum process systems on offshore installations. These process systems require power to operate the separation and compression processes involved in refining the produced petroleum.

Typically, these processes are powered by gas turbines, explained in greater detail in chapter 2.2. Gas turbines use some of the produced gas to generate electricity and mechanical power, while also generating carbon emissions. These gas turbines are thus a major source of carbon emissions in the extraction of oil and gas. Finding a more suitable and, more importantly, renewable alternative energy source to gas turbines can be a possible method to reduce overall carbon emissions from offshore oil and gas production.

A potential renewable energy source for an offshore installation is wind power. Offshore wind farms powering process systems at oil and gas platforms could possibly be the key to reducing overall carbon emissions from offshore oil and gas installations.

This thesis will carry out an analysis of the power consumption of an offshore process system by building a comparable model of such a system. Then, an analysis of the power generation capabilities of an assumed offshore wind farm, based on real-life wind data from an existing offshore production facility, will be carried out to determine whether an offshore wind farm can be a viable alternative to gas turbines. The main objective of this thesis will be to answer the following research question: *Can offshore wind power be an effective alternative to gas turbines as a source of electrical power to operate offshore process systems?*

1.3 Structure

This study aims to answer the research question through modelling and analysis. These are detailed in the following chapters:

Chapter 2 - Background presents the necessary background information needed to understand the context of this thesis. Relevant information regarding green energy transitions, topside processing systems and offshore wind farms is included in this chapter.

Chapter 3 - Modelling a processing system describes the process of building a model of an offshore processing system. This chapter will describe, in detail, both the software and the methodology employed to build a working model of a processing system for the refinement of petroleum. Descriptions of the components as well as their mechanics are also detailed in this chapter.

Chapter 4 - Energy mapping includes the power consumption data of the model as well as an analysis of the power generation capabilities of existing offshore wind farms. This chapter will entail mapping the energy generation of the wind farms with the energy consumption of the process model. Further analyses regarding the production capacity and flexibility of the processing system will also be detailed in this chapter.

Chapter 5 - Discussion presents a discussion of the results achieved through the various analyses conducted in chapter 4. The feasibility of these results, in a real-world scenario, will also be discussed.

Chapter 6 - Conclusion presents the concluding remarks regarding the work done in this thesis and gives a final answer to the research question mentioned in chapter 1.2.

Chapter 7 - Future work highlights the possibilities for further research that can be carried out on the basis of the work presented in this thesis. This chapter will also include specific areas of research that can directly benefit from the contents of this thesis.

2 Background

2.1 The Green Shift

The term 'the green shift', popularized in Norway back in 2015, is often used to represent the political, economical and cultural change in Norway to become a low-emission country by the year 2050 [6]. While there is no clear definition of the term, it generally implies an overall change towards becoming a more environmental-friendly society according to the United Nation's sustainability goals. The term has gained increasing relevance as a direct result of the global environmental and climate challenges. It is used as a broader term for the reorganization of society as well as a more specific term for changes in certain areas [7]. In the first case, the green shift involves a transition to a society where growth and development take place within the limits of nature. In the second case, it is a transition to products and services that have fewer negative consequences for the climate and the environment than today.

A Norwegian commission, appointed by royal decree, to study the possibilities of reducing emissions concluded in a 2006 report [8] that it will become necessary for Norway to reduce overall carbon emissions by the year 2050 to avoid irreparable damage to the environment. The report states that these damages can be avoided and that it is "possible, and not extremely expensive, to reduce Norway's carbon emissions by 67% within the year 2050".

While technologies now exist to achieve the goal of reducing overall carbon emissions, significant investments are required to further develop sustainable solutions to the emissions problem. This means greater allocation of funds for research and development, as well as investments in new green start-up companies [9]. It has now become the combined responsibility of the government, business and investors to provide the funds necessary to achieve the changes needed to reduce emissions by 2050.

The market for green technology companies is still growing and there is always great uncertainty associated with which solutions and companies succeed. This poses a high risk to investors. However, investors have shown a great willingness to invest capital in order to contribute to Norway's restructuring towards a highly environmental-friendly society [9]. Figure 2.1 presents the data for investments in renewable energy in Norway from 2006 to 2020:

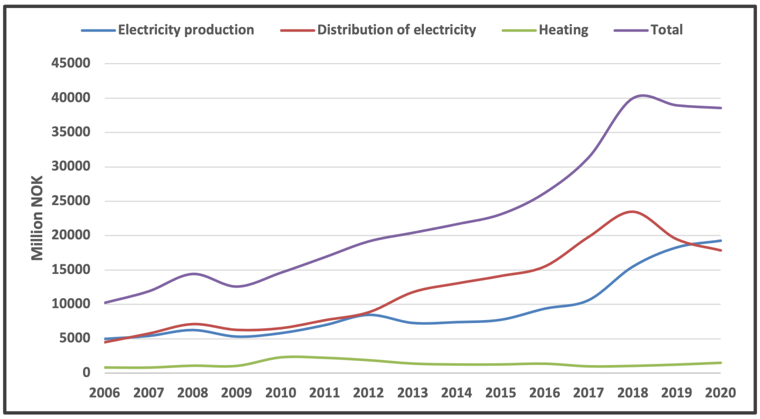


Figure 2.1: Investments in renewable energy from 2006-2020 [10]

The investment trends shown in figure 2.1 highlights the commitments of all investors involved in reducing carbon emissions in Norway. Steady and increasing investments since 2006 have led to a significant increase in the renewable energy sector in Norway. This increasing investment trend is also witnessed in Norway's electricity production. Currently, Norway produces roughly 90% of its electricity through hydroelectric power [11]; however, Norway has experienced an increase in electricity production from wind power, as shown in figure 2.2.

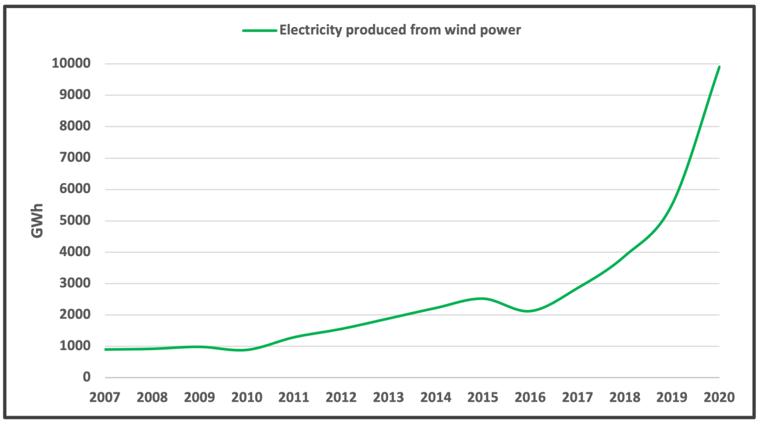


Figure 2.2: Electricity production from wind power from 2007-2020 [12]

This trend of electricity production from power equates to an increase of over 1000% from 2007 to 2020. There are two main reasons attributed to this increasing trend. The first of which is government incentives for both new and existing energy companies to utilize renewable energy. As the country aims to meet its emission goals for 2050, the government has taken a more active role in the integration of renewable energy within the energy sector [13].

The second reason stems from the costs associated with carbon emissions. In Norway, CO_2 emissions are taxed at a fixed rate per tonne. This rate stood at 591 NOK ($60.2 USD) per tonne CO_2 in 2021 [14]. This carbon tax is fixed across all industries. Thus, integration of, or investment in, renewable energy can be a potential method to reduce operating costs. This reason for increased electricity production from wind power, however, is only associated with companies and industries that are able to reduce carbon emissions without sacrificing operational or production capacity [13].

The trends shown in figures 2.1 and 2.2 clearly indicate that there is a genuine and concerted ongoing effort in Norway to significantly reduce carbon emissions. If these trends continue on their current trajectory and if renewable energy is integrated into industrial processes on a larger scale, Norway may then be able to achieve its goal of emission reduction by 2050 and go through a successful green shift.

2.2 Topside processing systems

The word topside refers to the facilities and equipment at an offshore oil and gas field that are installed and operated above the waterline. Topside structures are usually modular, and are installed onto either a fixed or floating underwater structure [15]. Topside processing systems are some of the modules of the total topside. These systems carry out several critical operations, such as the separation of oil and gas, power generation, providing living quarters, facilitating water or gas injection and carry important equipment required for operations related to safety, drilling and production [16].

Topside process systems separate oil, gas and water from the raw petroleum by consuming power and heat. The power is produced by gas turbines driven by some of the produced gas, or heavy oil or diesel [17]. Heating is provided either by using gas burners, recovered waste heat or electric heaters [18]. Figure 2.3 gives an overview of the processing and utility plants at offshore facilities:

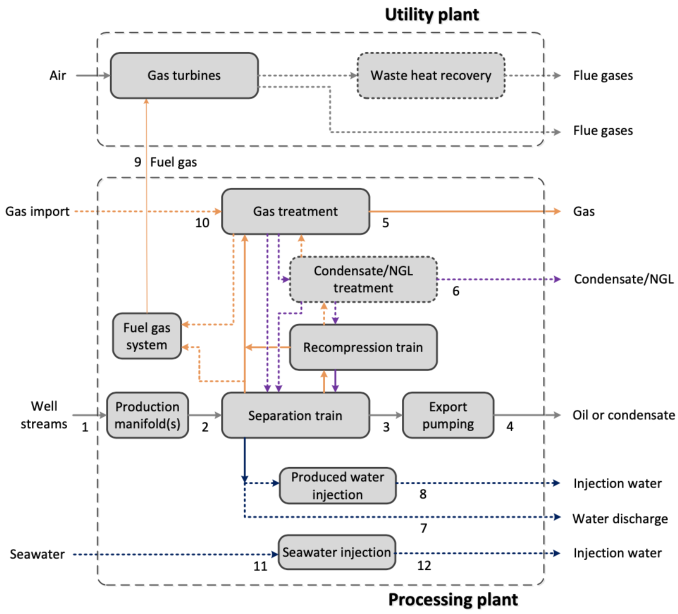


Figure 2.3: General overview of the processing and utility plants [17]

The produced petroleum fed into the process system is a complex multi-phase fluid. It contains a wide range of chemical components, from light hydrocarbons in the gaseous form, such as methane, to heavy hydrocarbons in the liquid phase, such as cycloalkanes, and is extracted along with subsurface water [19]. The goal of the processing plant is to separate the different phases to meet the different production demands set by the operating company, and to reach the maximum possible production rates of oil and gas.

In the processing system, the produced petroleum enters one or several production manifolds in which the fluid streams are mixed and the pressure reduced to ease separation between the liquid and gaseous phases [18]. The stream(s) of petroleum is fed into a separation system where oil, gas and water are separated primarily by gravity in separation tanks. The crude oil flowing out of the separation tank enters a treatment and export pumping section. The gas leaving the separation enters the re-compression stage. Here, it is cooled and sent to a scrubber where condensate is removed, and re-compressed to the pressure of the previous separation stage. It is then sent to the gas treatment stage, where it is purified [19]. The gas may be compressed for export to the shore, used for lift or as an injection fluid to improve the recovery rate.

The condensate removed from the re-compression and gas treatment stages is either sent back to the separation stage and mixed with crude oil or processed in a condensate treatment section. Water separated from the petroleum enters a wastewater handling train, in which particulates and dissolved hydrocarbons are removed [19]. It is then either discharged back into the sea or enters an injection stage where it is further cleaned and pumped to a high pressure level. In parallel, seawater may be processed on-site for further injection into the reservoir for enhanced oil recovery or may be used for cooling purposes within the process system [17].

This process system is powered, as stated previously, through electricity and mechanical power generated by gas turbines. These gas turbines generate power from the combustion of natural gas in a combustion chamber, much like how internal combustion engines in cars function. Gas turbines consist of three main components. These are the gas compressor, combustion chamber and turbine. The process begins with the funnelling of natural gas through the compressor. The high pressure gas then combusts in the combustion chamber and the energy that is released from this combustion drives the turbine [20]. The gas turbines are connected to a generator that converts the mechanical power from the turbine to electrical power [21].

Gas turbines provide electrical power to the entire offshore installation, not just the processing system. This dependency on gas turbines results in significant amounts of carbon emissions from the whole process of extraction to refinement, as shown in figure 2.4. A large share of these emissions are attributed to the operation of gas turbines, but the remaining portion of emissions are associated with gas flaring and diesel combustion [21].

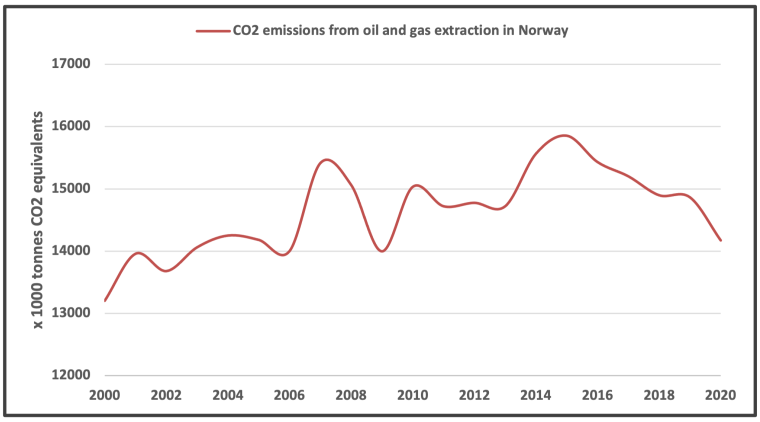


Figure 2.4: CO_2 emissions from oil and gas extraction in Norway from 2000-2020 [22]

The energy consumption and emissions associated with oil and gas production differ from one field to another. The consumption and emission numbers depend on the field conditions, e.g. crude oil temperature, export specifications, e.g. purity and pressure requirements, and the lifetime of the field itself [21]. Various strategies can, in the meantime, be applied to improve the overall energy performance of offshore oil and gas installations. These strategies range from improving energy generation efficiency, reducing energy intensive processes and integrating either renewable energy or energy recovery systems [23]. These strategies function as a means to reduce overall carbon emissions from the extraction and refinement processes of offshore oil and gas installations.

2.3 Offshore wind power

The generation of electricity from wind farms in bodies of water, usually at sea, is known as offshore wind power or offshore wind energy. This renewable energy is obtained by taking advantage of the force of the wind that is produced at sea, where wind speeds are generally greater than on land due to the absence of natural barriers.

According to the International Energy Agency, offshore wind could become the largest source of electricity in Europe and account for 20% of all electricity production by 2040 [24]. The race for market share has already begun. Both the European Union and the United Kingdom are planning large-scale development, with 350 GW and 50 GW in the North Sea by 2030 [25][26], respectively.

There has been a significant increase in the investment in offshore wind power within Europe. European countries in 2020 invested a combined total of €24.2 billion in offshore wind power which financed a total of 7.1 GW in new power generation capacity [27], as shown in figure 2.5.

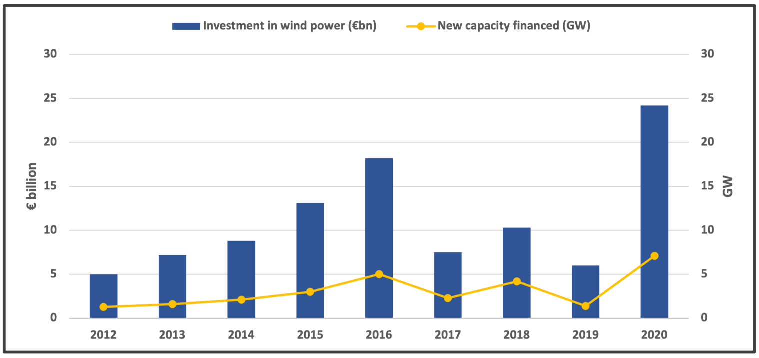


Figure 2.5: European offshore wind investments and capacity financed from 2010-2020 [27]

Norway, on the other hand, is falling behind in the race for offshore wind energy. But there is a reason for its absence in the offshore wind energy market. Virtually all of the offshore wind farms that have been developed or are being developed in the world today are fixed, or grounded, to the seafloor. An analysis by the Norwegian Water Resources and Energy Directorate [28] shows that it costs more to build fixed offshore wind farms in Norway than in other European locations where fixed offshore wind farms currently exist.

The main reason for this increased cost is the greater water depth and the geological complexity of the seabed on the Norwegian Continental Shelf. The water depth alone increases the costs of installing an offshore wind farm substantially. Due to this, the only viable option for Norway is a floating offshore wind farm. However, floating wind farms are still significantly more expensive than the fixed wind farms installed by other European nations [28].

If Norway aims to integrate renewable wind power from offshore wind farms with the extraction of oil and gas, significant investments have to be made to achieve this goal. Floating wind farms are, currently, the only viable option for Norway and such offshore wind farms supplying renewable energy to its many offshore installations can be the big step needed to becoming a low-emission, environmental-friendly country.

3 Modelling a processing system

3.1 K-Spice

The software used for modelling the process system was K-Spice. K-Spice is a dynamic process simulation tool that can be used to design a process system for oil and gas separation. Designed and built by Kongsberg Digital, K-Spice can be used to plan start-up of a processing plant, determine optimal operation of components and improve overall efficiency of a processing plant.

Being a *dynamic* simulation tool, K-Spice was ideal for this project as testing the model for the necessary readings requires real-time data. The dynamic aspect of K-Spice provides every piece of information for each model variation in real-time and also shows how each component within the model adapts to these variations.

K-Spice also provides the data for the components' power consumption in real-time. This feature is especially useful as the main goal for building this process model, as stated, is to study the power consumption of the model and how the consumption is affected by the variations in the production rates. All data presented in this chapter was acquired through model testing in K-Spice.

3.2 Model description

The model built in K-Spice was designed to be a close approximation of a typical topside processing system. It has three separation stages, each at varying pressures to induce separation. Each separation stage also includes components such as heat exchangers, scrubbers and compressors. The functionality and purpose of these components are detailed further below. A complete process flow diagram of the model is shown in figure A.1 in Appendix A. In this diagram, each component is labelled and will be referenced throughout this section.

The first component of the model that was built were the feed inlets (components 1.A and 1.B). These inlets are how the produced petroleum is fed into the separation system. K-Spice provides a generic fluid composition that can be used to simulate the produced petroleum. The composition of the petroleum is given in table B.1 in Appendix B. As the primary goal with this model was to extract power consumption and load management data, the inlet conditions of the produced petroleum were set to the default values of K-Spice. These values were a temperature of 55°C, a pressure of 50 bar and a total incoming mass flow rate of 534 500 kg/hr.

As the model was designed to have three separation stages, three separators (components 2.A - C) were built for the model. Each separator had the exact same dimensions, with a length of 5 meters, diameter of 3.5 meters and a height of 1.5 meters. These dimensions were the default separator dimensions of K-Spice and were used for the sake of simplicity. The first two separators were three-stage separators, meaning that they were separating oil, gas and water. The third separator was only a two-stage separator, separating just oil and gas. The pressure in each separator was kept constant at 25 bar, 6 bar and 1.5 bar, in separator 2.A, 2.B and 2.C respectively. Decreasing the pressure at each separation stage leads to the lighter carbons flashing from the liquid to the vapor phase [29]. This meant that by lowering the pressure at each stage, more gas could be separated from the oil.

Heat exchangers (components 3.A - C) are used in processing systems to cool down the gas before the compression stage. This is done to ensure that the gas does not overheat as compression of a gas leads to a higher gas temperature, and also to promote liquid condensation and dropout in order to ensure that the inlet to the compressor does not have any liquid. Each heat exchanger is identical to one another. As gas passes through the heat exchanger, cold water is also passed through. The water has a constant temperature of 15°C and cools the gas down to 30°C. In order to keep the gas outlet temperature constant at 30°C, a control valve is used on the water outlet. The valve is controlled to let the water out of the heat exchanger only if the outlet records a gas temperature of 30°C.

The gas is then led to the scrubbers. Scrubbers (components 4.A - C) are used to further separate any residual condensates that are mixed with the gas. After passing through the heat exchanger, some of the gas will tend to condensate due to the decrease in temperature. Scrubbers can also remove residual water contained in the gas as result of condensation. These scrubbers can be thought of as vertical separators for the separation of condensates from gas. From the scrubber, the gas moves to the compressor, while the condensates are transported to the oil outlet from the separator where they are mixed with the oil coming out of the separator.

Compressors (components 5.A - C) are used to increase the pressure of the gas before the final gas outlet. Gas outlets tend to have much higher pressures than at the inlets, and so the gas must be compressed to achieve this higher final pressure. The goal was to compress the gas to an initial pressure of 50 bar, after which the gas would pass through a final compressor, detailed in chapter 3.4.1. As each separation stage lowers the pressure of the gas, each compressor has to increase the pressure of the gas to the same pressure as the previous stage. This meant that the second compressor had to increase the gas pressure from 6 bar to 25 bar, and the third compressor had to increase the pressure from 1.5 bar to 6 bar. Compression of the gas, at each separation stage, to the pressure of the previous separation stage ensures that the compressors do not consume significant amounts of electrical power. Once the gases are at equal pressure levels, they are mixed together for further re-compression. Through this system of re-compression, the overall power consumption can be reduced as the compressors do not have to compress the gas at each level to the final outlet pressure.

In order to prevent the compressors from overworking/surging, an anti-surge loop (components 6.A - C) was built for each separation stage. This loop acts as a deterrent should the compressor not be able to handle the compression required or if the flow rate becomes too small such that the compressor starts to surge. The anti-surge loop, in that case, redirects any excess flow back to start of the loop. The anti-surge loop is operated by a transmitter connected to the compressor. When the compressors begins to surge, the transmitter sends a signal to the anti-surge valve to open. The valve, in case of surging, does not automatically open to its fully open setting of 100%. Instead, the transmitter controls the opening of the valve to allow just enough gas to pass through the anti-surge loop to stabilize the compressor. Ideally, the anti-surge loop should remain closed if the compressors are correctly configured and thus function as a safety mechanism. The configuration of the compressors is discussed further in chapter 3.3.

An oil pump (component 7) was connected to the outlet of the third separator. The purpose of the pump was to increase the pressure of the oil from the separator before it reached the final oil outlet. The oil pump was configured to increase the pressure of the oil from 1.5 bar, which was the pressure inside the third separator, to 50 bar, which was the desired oil outlet pressure. Configuration of the oil pump is detailed in chapter 3.3.

3.3 Compressor configuration

The main challenge with building this model in K-Spice was achieving the correct compressor configuration. Correct configuration was necessary to achieve the desired pressure levels but also ensure that all the compressors were operating at an optimum level.

As these components were not correctly configured initially when built, there were some issues that appeared as a result. The main issue was backflow throughout the system. Backflow is a term for flow moving in the opposite direction than the desired direction. This was caused by an increase in the pressure differential from the starting point to the end point. Flow will naturally occur from an area of higher pressure to an area of lower pressure [30], thus backflow occurs when the pressure differential drops from the inlet to the outlet. Essentially, backflow is a direct consequence of incorrect configuration of the components, specifically the components' pressure levels, between which gas is intended to flow.

Configuration of the compressors was done by adjusting the components' values for nominal polytropic head, nominal flow rate and rotational speed. The polytropic head of a compressor is a function of pressure ratio across the compressor [31]. Therefore, an increase in the the polytropic head will increase the outlet pressure of the compressor, assuming that the inlet pressure remains constant. The nominal flow rate value determines the initial operating point of the compressor by assuming the volume flow rate at the inlet. Naturally, entering a close approximation of the inlet volume flow rate will lead to the compressor being able to handle the workload better. Finally, the rotational speed of the compressor defines the maximum operating capacity of the compressor. If the compression workload requires rotational speed greater than the given value, the compressor will malfunction.

Correctly configuring the compressors through these values was done essentially through trial and error. K-Spice, by default, gives preset values to all configurable variables when a new component is built. Thus configuring the compressors required altering each of the values separately and determining the impact of the changes by looking at the compressor's head-flow map, shown in figure 3.1. This meticulous process of configuring the compressors was done for each of the compressors separately as each compressor was required to compress the gas to various levels.

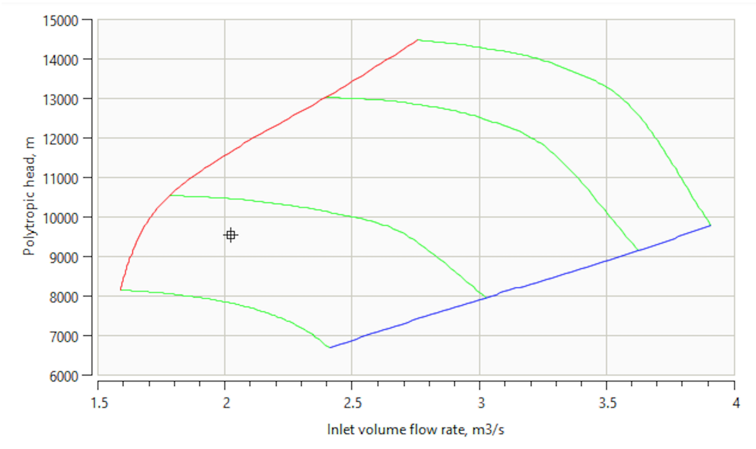


Figure 3.1: Head-flow map of a compressor operating normally in K-Spice

The head-flow map, shown in figure 3.1, is drawn by K-Spice using the given values for polytropic head and inlet volume flow rate. The operating point of compressor (the small black point on the map) moves around the map in real-time. Correctly configuring the compressor would then involve getting the operating point to stabilize within the limits of the map, i.e. in between the red and blue lines.

3.4 Additional components

In order to replicate a real-life processing systems, some additional components were added to the model. These components were a fourth compressor, an oil tank and a gas pipeline. They all serve specific functions in a processing plant, discussed further below in this chapter.

3.4.1 Fourth compressor

A fourth compressor (component 8) was added to further increase the gas pressure from 50 bar, after compressor 5.A, to a final gas outlet pressure, i.e. the gas delivery pressure, of 200 bar. After initial testing, it became apparent that a single compressor would not be sufficient to increase the gas pressure from 25 bar to 200 bar. Another round of compression was required to achieve this outlet pressure. This fourth compressor was configured in the same manner as discussed previously in chapter 3.3.

Compressing the gas to the outlet pressure of 200 bar required the addition of another heat exchanger similar to the heat exchangers mentioned in chapter 3.2. This heat exchanger (component 3.D) was placed between the two compressors (components 5.A and 8) to once more cool the gas to 30°C before re-compression in order to avoid overheating.

3.4.2 Oil tank

An oil tank was added to the model to replicate the oil storage facilities of an offshore processing plant. The oil tank (component 9) was simulated by adding a horizontal, cylindrical drum between the third separator (component 2.C) and the oil pump (component 7). An oil bypass flow line was also added to direct the oil straight to the pump from the separator. This negated the need for the oil to pass through the tank when oil storage is not needed.

An arbitrary volume of 500 000 bbl ($\approx$ 80 000 m^3) was assigned to be the capacity of the tank, as well as an arbitrary length of the tank of 100 meters. K-Spice allows for user-defined dimensions of certain components, and so creating an oil tank of a specific volume required values for both length and diameter. Thus, a calculation using the formula for the volume of a cylinder, shown in equation 3.1, was done to determine the necessary diameter needed to achieve the desired volume.

$$\begin{aligned} V &= \pi \times \left(\frac{d}{2}\right)^2 \times L \\ \implies d &= 2 \times \sqrt{\frac{V}{\pi \times L}} \\ \implies d &= 2 \times \sqrt{\frac{80000}{\pi \times 100}} \approx \mathbf{32\ m} \end{aligned} \tag{3.1}$$

3.4.3 Gas pipeline

Gas pipelines are used to transport the produced gas from the offshore processing plant to the onshore distribution point. For the model, the pipeline was also simulated using a cylindrical drum. Unlike the oil tank mentioned previously in chapter 3.4.2, there was no need to add a gas bypass flow line as the gas has to pass through the pipeline, after compression, to the final outlet.

The pipeline was designed with an arbitrary length of 50 km and an arbitrary pipe diameter of 30 inches (≈ 0.762 m) were used to calculate the total volume of the gas pipeline. This calculation is shown below in equation 3.2.

$$\begin{aligned} V &= \pi \times \left(\frac{d}{2}\right)^2 \times L \\ \Longrightarrow V &= \pi \times \left(\frac{0.762}{2}\right)^2 \times 50000 \approx \mathbf{22800\ m^3} \end{aligned} \tag{3.2}$$

3.5 Load flexibility

As the aim of this thesis is to determine if wind power can be an effective source of power for a processing system, testing the model's adaptability regarding varying workloads is paramount. This test is also important due to the unpredictable and varying nature of wind power. The model must be able to operate under unstable supply of power by reducing or increasing its production output without any malfunctions.

The model's adaptability to varying production rates was first tested. When the production rate is reduced, overall power consumption of the model is reduced as there is a smaller workload for the compressors and oil pump. Likewise, when the production rate is increased, the workload is increased leading to greater power consumption. During times of a power surplus, i.e. more available power generated from wind, the production rate of the model can be increased to utilize this extra power. During times of a power deficit, i.e. less than optimal power generated, the production rate can be reduced to lower overall power consumption.

This test was initially designed to be carried out by using the oil tank to vary production rate. This proved to be a difficult challenge due to the difficulty of using advanced controllers in automating the process of directing the oil either through the tank and storing it, thus reducing the production rate, or directing the oil through the bypass flow line to maintain the production rate. Another issue was that using the oil tank did not present any means to increase the production rate beyond the starting value of 534 500 kg/hr. Any increase in the production rate would have to be done at the feed inlets.

The solution to this issue was to not use the oil tank at all, but instead use an in-built K-Spice function called 'source mode'. This function allows the user to enter specific values for all properties of the production fluid, such as temperature, pressure, enthalpy and flow rate. The ability of source mode to specify a particular flow rate was used to simulate varying production rates. Source mode can be used on any component, and so was used on the feed inlets to test how the model adapts to changes in the incoming mass flow rate.

Since the default value for the production rate was 534 500 kg/hr, it was defined as the 'design' rate, meaning that this particular flow rate equates to 100% production. The flow rate value was then altered in 10% increments in both the positive and negative directions until the limits of the model were reached. The results of this test are given below in table 3.1.

Table 3.1: Load flexibility test results

Total production rate percentage (%)	**Total production rate ($\times 10^3$ kg/hr)**
50	267.3
60	320.7
70	374.2
80	427.6
90	481.1
100	534.5
110	588.0
120	641.4

The test results show that the model is able to operate within a range of 50% to 120% of the design flow rate. The model was unable to operate without active surge control and no further reduction in power consumption was observed when flow rates beyond these limits were used. Figure 3.2 shows the production rates of oil, gas and water, as well as the total production rate throughout this test of the model's load flexibility.

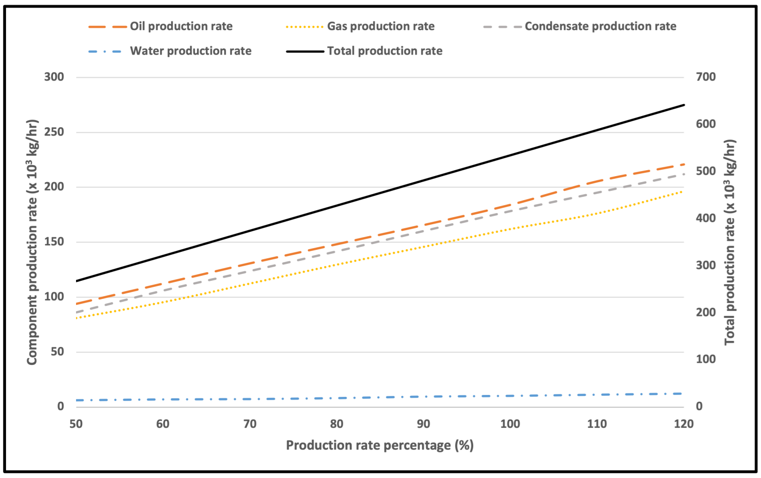


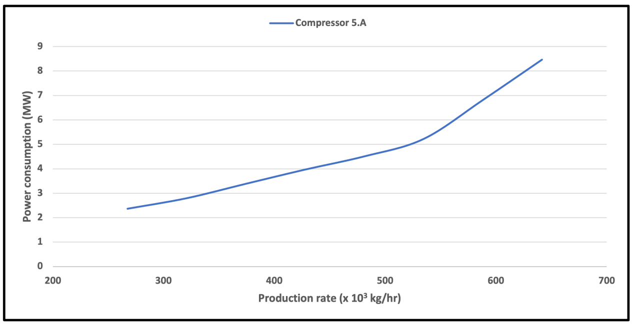
Figure 3.2: The production rates of oil, gas and water and the total production rate

From figure 3.2, it can be seen that the production rates are generally linear for all components. However, the production ratio of condensates to gas is smaller at production rates lower than 100% than at production rates greater than the design rate, i.e. more gas is produced at lower production rates. During these lower production rates, a decrease in the separator pressures was observed. As mentioned in chapter 3.2, lower separator pressure leads to more gas separating from the oil. This may be the reason for the greater difference between gas and condensate production at higher production rates than at lower production rates.

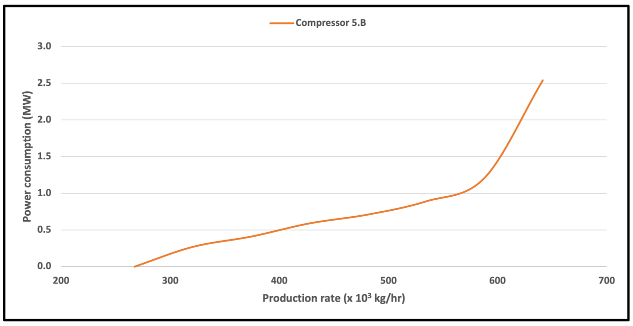
4 Energy mapping

4.1 Power consumption of the process model

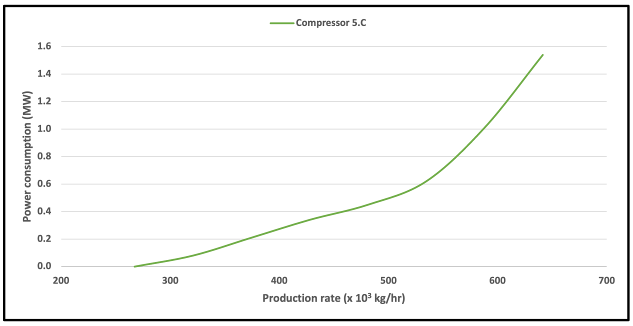
After modelling the process system, the next stage was to extract its power consumption data. As stated in chapter 3.1, K-Spice provides the power consumption data of each components that is operated using electrical power in real-time. These components were the four compressors and the oil pump. The power consumption of each of these components was noted when the production rate was altered to the values shown in table 3.1. The power consumption data for the four compressors are shown below in figure 4.1.



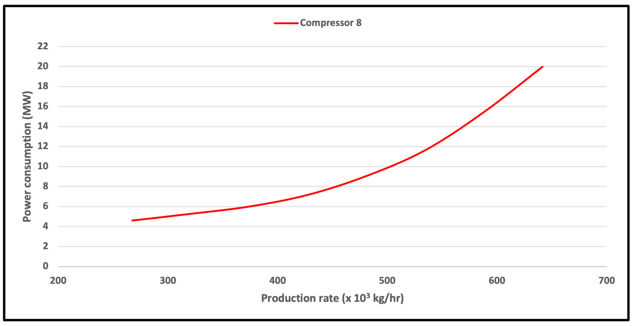
(a) Power consumption of compressor 5.A



(b) Power consumption of compressor 5.B



(c) Power consumption of compressor 5.C



(d) Power consumption of compressor 8

Figure 4.1: Power consumption of all four compressors under varying production rates

It is worth noting that the power consumption of compressors 5.B and 5.C, shown in figures 4.1b and 4.1c respectively, is 0 at the lowest production rate of 50%, or 267 300 kg/hr, of the design rate. This could possibly be a result of their individual configuration. In order to achieve the correct configuration of these compressors for the design production rate of the model, their values for the nominal inlet volume flow rate were set to lower than that of the other two compressors. This meant that once the production rate was reduced to the minimum level, the actual inlet volume flow value of these compressors was nearly 0. K-Spice therefore assumes that there is insufficient flow for the compressors to operate normally, thus rendering the compressors inoperative. In this case, the gas would simply pass through the compressors and reach the next functioning compressor without any previous compression. As a result, compressor 5.A had to compress the gas from a lower initial pressure than the 25 bar initial pressure it was intended to compress. This, in turn, meant that compressor 5.A, shown in figure 4.1a, had a higher consumption at this particular production rate than it would have if the other two compressors were operating.

The other component that required electrical power to operate was the oil pump. The power consumption of the oil pump, in the same manner as with the compressors, was also noted for each production rate value. The data for the power consumption of the oil pump is presented below in figure 4.2.

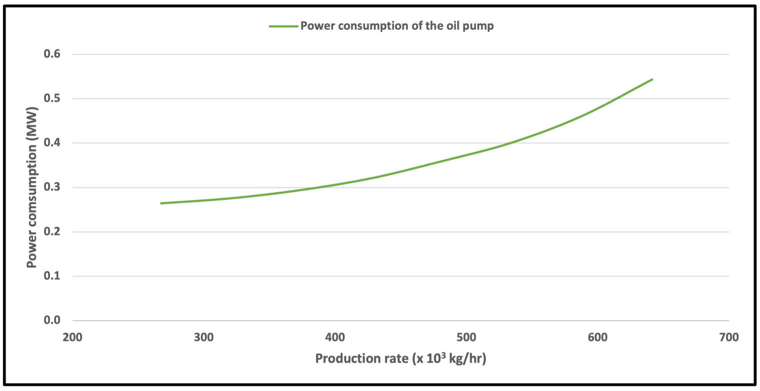


Figure 4.2: Power consumption of the oil pump under varying production rates

The overall power consumption of the oil pump is significantly lower than any of the four compressors. In order to understand why this is the case, first a distinction has to be made between a compressor and a pump. While both are considered as open systems, they are used for different types of fluids. Generally, compressors are used to increase the pressure of a gas and pumps are used to increase the pressure of a liquid. Then, and application of the first law of thermodynamics for the work done within an open system, shown below in equation 4.1, is needed:

$$W = \int v \, dp \tag{4.1}$$

Here, the work done, W, is calculated using the specific volume of a fluid, v, across a pressure differential. The specific volume of a liquid is lower than the specific volume of a gas [32]. Therefore, the work done by a compressor is greater than the work done by a pump across the same pressure differential. Since work represents the amount of energy transferred when carrying out an action, the power consumption of a system can be equated with the work done by the system. Thus the power consumption of a pump is lower than the power consumption of a compressor, as shown in figures 4.1 and 4.2.

The final step in extracting the power consumption data is to combine the power consumption of all components to create a consumption profile of the model. Adding each component's consumption at every production rate values gives the total power consumption of the model. The data for the total power consumption of the model is presented in table 4.1.

Table 4.1: Power consumption of the model

Total production rate ($\times 10^3$ kg/hr)	**Power consumption (MW)**
267.3	6.37
320.7	8.71
374.2	10.54
427.6	12.44
481.1	14.93
534.5	18.80
588.0	24.91
641.4	33.06

From the data presented in table 4.1, the power consumption range of the model can be extracted. The model requires 33.06 MW, at the maximum production level, and, at the lowest production level, 6.37 MW to operate normally. This consumption range of 33.06 MW to 6.37 MW will be used further in chapter 4.3. The data presented in table 4.1 is then used to create the power consumption profile of the model, shown below in figure 4.3.

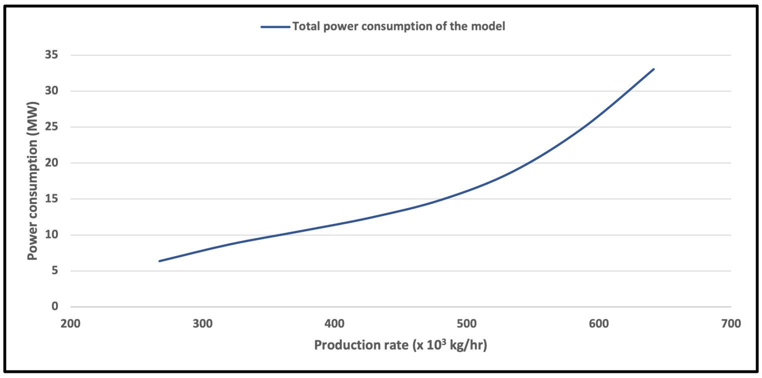


Figure 4.3: Total power consumption of the model under varying production rates

It can be seen in the consumption profile, figure 4.3, that there is a slight decrease in power consumption at the lowest production level of 50% production, or 267 300 kg/hr. This decrease is directly related to the previously discussed 'shut-down' of compressors 5.B and 5.C. These two compressors were inoperative at this production level, and did not, therefore, contribute to the total power consumption. Had these compressors been operative, the consumption profile would have straightened off towards the lowest production level. Since this model is a simulation of a processing system, it was still able to function as needed without two of its four compressors. In a real-life case, this would be unacceptable and the operating limits would have to be altered.

4.2 Wind power generation at Gullfaks E126

Gullfaks E126 is a section of the greater Gullfaks oil field located in the Tampen region, located in the northern region of the North Sea. Production of the Gullfaks field started in 1986 with the construction of three integrated platformed called Gullfaks A, B and C. The production facility includes a processing plant for the separation of oil and gas. Being predominantly an oil field, Gullfaks had proven oil reserves of roughly 388.2 million Sm^3 and 23.1 million Sm^3 of proven gas reserves. Today, Gullfaks is nearing its end-of-life stage with only 14.3 million Sm^3 of oil reserves left [33].

Wind data gathered at Gullfaks E126 for the entirety of 2015 was provided by SINTEF. The data provided the potential electrical output of a wind power installation at Gullfaks E126. The data was given as hourly readings for the entire year. For the purposes of this thesis, only the data for January was used to create a useful power generation profile of a potential wind farm. As there are a total of 744 hours in the month of January, a wind power profile consisting of 744 data points was created to demonstrate the power generation capability of an offshore wind farm located at Gullfaks E126. This power generation profile is shown in figure 4.4. This power generation profile is further used in chapter 4.3 for a comparison with the power consumption of the process model. The graph in figure 4.4, as well as the figures presented in chapters 4.3 and 4.4, was created using a timescale of one month, i.e. the month of January in 2015, with each measurement taken at every hour during that month.

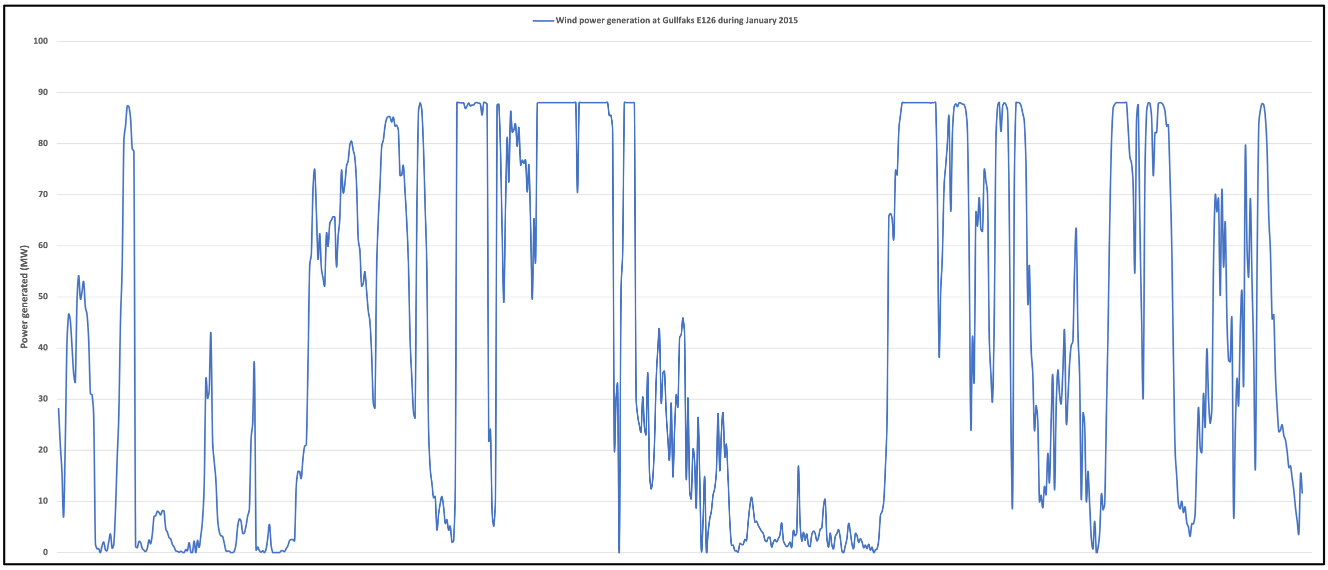


Figure 4.4: Wind power generation capabilities at Gullfaks E126 during January 2015

4.3 Mapping power consumption with power supply

The next step in the energy mapping process is to map the power consumption of the model to the wind power generation at Gullfaks E126. To achieve this, a maximum possible consumption value has to be determined in order to match the available power. This was done by creating a Python code that is given in Appendix C as code 1.

This Python code starts by extracting the available power data shown in figure 4.4 as well as the power consumption range presented in table 4.1. Then, the code determines the maximum possible power consumption of the model based on the available power. This is done by defining three criteria for determining the power consumption. The first criterion handles those hours of power generation where the available power is greater than the maximum consumption of the model. If the available power is greater than the maximum consumption, or 33.06 MW, then the power consumption will be set to 33.06MW. The second criterion handles the hours when the available power is within the operating consumption range of the model, i.e. between 33.06 and 6.37 MW. The power consumption is then set to equal the available power. Lastly, the third criterion handles the hours where the available power is less than the minimum consumption. In those cases, the power consumption is set to the minimum level, or 6.37 MW, because reducing the consumption beyond this point would surpass the limits of the model, resulting in a lower production rate without any further reduction in power consumption. Here, an assumption is made that when the available power is less than the minimum consumption of the model, the gas turbines would be utilized to power the processing system such that production can still continue at the lowest possible power consumption level. The resulting power consumption values are then extracted to an Excel file. Figure 4.5 shows the mapping of power consumption values, obtained from code 1, with the available power, previously shown in figure 4.4.

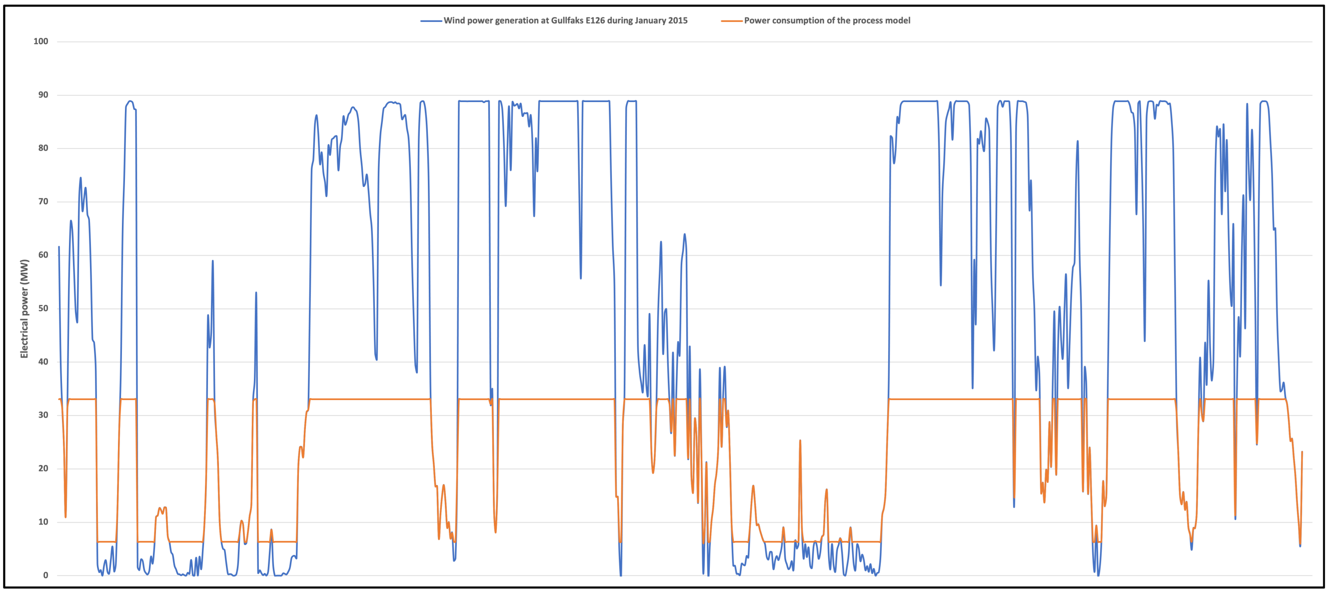


Figure 4.5: Mapping the power consumption of the model with the power generated at Gullfaks E126

As it can be seen in figure 4.5, there is significantly greater number of hours when the available power is greater than the consumption than when the available power is less than the consumption. Overall, there is a greater surplus of available power. The exact values for power surplus and power deficit are given in table 4.2.

Table 4.2: Power difference data

Power surplus (MWh)	**Power deficit (MWh)**	**Power difference (MWh)**
+ 14 190.1	- 799.4	+ 13 390.7

For the calculation of the values presented in table 4.2, a difference between the available power and the power consumption was calculated for each hour. Power surplus was calculated by the summation of all positive power differences, i.e. when the available power was greater than the consumption. Power deficit was calculated by the summation of all negative power differences, i.e. when the available power was less than the consumption. Power difference is simply the the difference between power surplus and power deficit.

This data shows that there is more than sufficient power generated from wind and the potential possibilities of this finding is discussed further in chapter 5. However, a shortcoming of this finding is the power deficit value. As it can be seen through the power generation profile in figure 4.4, the available power varies, often quite substantially, every hour. There is very little to no stability in the supply of power. Processing systems require constant power and without a stable power supply, production capacity is severely limited. This shortcoming is also further discussed in chapter 5 and the possibilities for potential solutions to this issue are discussed in chapter 7.

4.4 Deriving production rates from power consumption

The final step in the energy mapping process was to create a profile of the production rate based on the power consumption of the model. Previously, power consumption was derived from altering the production rates, as mentioned in chapter 4.1. This meant that the power consumption was a function of the production rate. In order to derive the production rate from a known power consumption value, an interpolation of the production rate is needed.

An attempt was made at first to approximate a polynomial equation for the power consumption graph shown in figure 4.3. This proved to be quite a challenge as the graph did not conform to any order of polynomial equation, and even the closest approximations using a 5^{th} and 6^{th} order polynomial equation gave the incorrect values for power consumption the production rates given in table 4.1.

In order to solve this, another Python code was created to interpolate production rate from power consumption using the model's power consumption profile. This code is shown as code 2 in Appendix D. The code works by first extracting the data presented in table 4.1 from an Excel file. Then it determines, through piecewise linear interpolation, the value for the production rate for every power consumption value shown in figure 4.5. The calculated values for the production rate are then extracted to another Excel file. These production rates were then mapped alongside the power consumption values, shown in figure 4.5, and the results are shown below in figure 4.6.

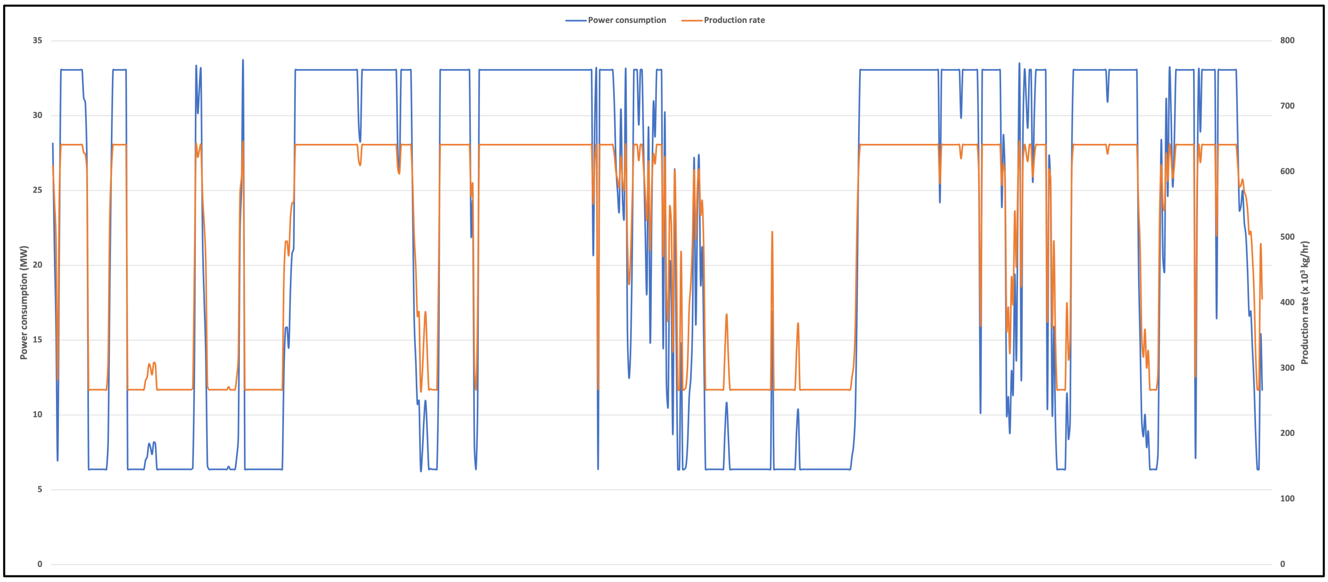


Figure 4.6: Mapping the production rate of the model with the power consumption

The mapping of the production rate and the power consumption shows how closely the production rate follows the changes in the power consumption. It can be observed that the number of hours with a stable production rate is lower than the number of hours where the production rate is varying. The potential consequences this has for the integration of wind energy as the power source of a processing system are discussed further in chapter 5.

5 Discussion

The aim of this study was to answer the following research question: *Can offshore wind power be an effective alternative to gas turbines as a source of electrical power to operate offshore process systems?* Based on the energy mapping and analyses shown in chapter 4, there are two aspects of wind energy, as the power source for a processing system, to consider in order to adequately answer the research question. The first is the wind power's capabilities as a power source and the second is the impact on production capacity with wind power as the main source of power.

Based on the wind data findings presented in chapter 4.2, electrical power generated from a potential wind farm at Gullfaks E126 would be more than sufficient to power the processing plant modelled in this thesis. The amount of power surplus generated from a potential wind farm at Gullfaks E126, given in table 4.2, is also an indication that wind power appears to be more than capable of supplying electrical power to the simulated processing plant. In fact, in 2020, a floating wind farm called Hywind Tampen consisting of 11 floating wind turbines was approved for construction to supply the Gullfaks field with electrical power [33]. This new wind farm, along with the power generation data presented in figure 4.4, highlights that wind power can be the main source of power for not only a processing plant, but an entire offshore production facility.

However, figure 4.4 also highlights the variability of wind power. The power output almost never remains stable and varies, occasionally, by a significant degree. The separation of oil and gas is a continuous process that requires a stable power supply to maintain the desired production output. Given the varying nature of wind power, it becomes practically impossible for the processing plant to operate at the same production level if the power supply suddenly drops below the minimum level. Therefore, the assumption made in chapter 4.4 that gas turbines may be utilized for powering the process system during times of a power deficit becomes vital. If gas turbines are used in combination with wind power, the production output remains stable. In that case, carbon emissions would not be fully eliminated but rather significantly reduced as times of power deficit are substantially less than times of power surplus.

The varying nature of wind power also affects the production rates of the processing system, as shown in figure 4.6. Hourly changes to the power generated by wind results in the processing plant either increasing or decreasing its production capacity to match its power consumption with the available power. As it has been shown by testing the model's load flexibility, in chapter 3.5, the process model is able to increase and decrease its production capacity without compromising functionality. Therefore, it can be assumed that a comparable, real-life processing system may be able to handle such variations in power supply should the need arise to either increase or decrease production output.

On the other hand, varying production rates may compromise the desired production levels as set forth by the operator of the field. In Norway, licenses to operate and produce oil and gas fields are given by the government to the various companies. As such, these companies then determine optimal production rates based on their revenue-cost projection as well as their clients needs [34]. And so achieving the desired production level becomes paramount for the operators. In the case of the process model's production output with a varying power supply, maintaining a steady production level is an immediate challenge that needs to be resolved. This challenge may be resolved by utilizing the oil storage tank, discussed in chapter 3.4.2. If an assumption is made that the desired production output demanded by the operator is equal to the design rate of the model, i.e. 100% production rate, then during times of a power surplus, the increased production of oil may be stored. This stored oil can then be extracted during times of power deficit such that the combined production output becomes equal to the desired production level even when the processing system has to reduce its production rate. Utilizing the oil tank in such a manner to achieve a stable production rate can thus be an effective solution to the challenges of a varying power supply.

6 Conclusion

This study was conducted with the aim of determining the feasibility of a method to reduce overall carbon emissions from the the Norwegian offshore oil and gas production facilities. This method involved swapping the power supply of offshore installations, which currently are gas turbines, with wind power and analyzing this change's effect on a processing system and its production output.

Based on the results gathered from the analyses of the process model's power consumption as well as the power generation data obtained from Gullfaks E126, it becomes quite clear that wind power generates more than enough electricity to power the process system. Despite the varying nature of wind, and by extension the varying nature of the power generated through wing, the total power generated over a period of one month can quite comfortably supply power to the process system. But despite the substantial power surplus during maximum power generation, there are still times during the month where available power is insufficient to power the process system, even when the system is at its minimum consumption level. The proposed solution of combining wind power with gas turbines might be the better alternative to negate the variability of wind power. Utilizing gas turbines only when wind power is insufficient will greatly reduce overall carbon emissions from the production of oil and gas at Norwegian offshore installations.

Furthermore, another challenge imposed by the variability of wind power, is the variability in production rates as the process system has to adapt its power consumption with the available power. This challenge can be overcome by utilizing the oil storage tank in order to maintain a steady production rate. Maximizing the production rate when there is a power surplus and then storing the extra produced oil will aid in maintaining a stable production rate when there is a power deficit. While production rates generally remain stable at either the maximum or minimum levels, variations in the production rates tend to last for only a few hours at a time. This implies that the process model only has to adapt to the variations for a short amount of time. This also further implies that oil would not have to be stored for too long at a time as minimum production level can continue for some time. Thus, utilizing the oil tank to counter the variations in production rates resolves the variability issue of wind power and proves that the challenges faced by the integration of wind power within the production of oil and gas are not insurmountable.

With the findings presented in this thesis, it can be concluded that offshore wind power can indeed be an effective alternative to gas turbines as a source of electrical power to operate offshore process systems. While the analysis of power output highlights the need for a combination of wind power and gas turbines to fully power a process system, the integration of wind power can result in a significant reduction in overall carbon emissions from the production of oil and gas. Integrating wind power with other offshore production facilities in Norway can be a big step for the country to reduce its carbon footprint and meet its goal of becoming a low emission, environmental-friendly nation.

7 Future work

Integration of wind power within the offshore production of oil and gas in Norway is still far from being reality. While projects such as Hywind Tampen [33] have been approved, new research into the areas such as energy storage and long-term production output will have to be conducted before a large-scale integration of wind power can occur.

Research into energy storage technology can greatly benefit from the work presented in this thesis. As shown in table 4.2, there is more than sufficient power generated from wind to power the process system. Technology that is able to capture and store this extra generated power can reduce the need for gas turbines all together. If these technologies are able to capture the excess power and store it for use when there is insufficient generated power, wind power can then become the sole power supply of an entire offshore production facility. This will eliminate most of the carbon emissions from the production of oil and gas.

Analysis of the long-term potential production of a process system powered by wind can also benefit from this work. This thesis presented the production rates for a single month when power is supplied by a wind farm without going into detail about the specific production numbers. Based on similar wind data shown in this thesis, an analysis of the specific production numbers can be carried out. This can further aid in assessing the production output under varying power supply conditions compared to the production output of a traditionally powered offshore installation. This analysis, with the use of either Excel formulas or Python programming, can determine the production potentials of both cases over the course of a field's entire or remaining lifetime.

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Appendix A

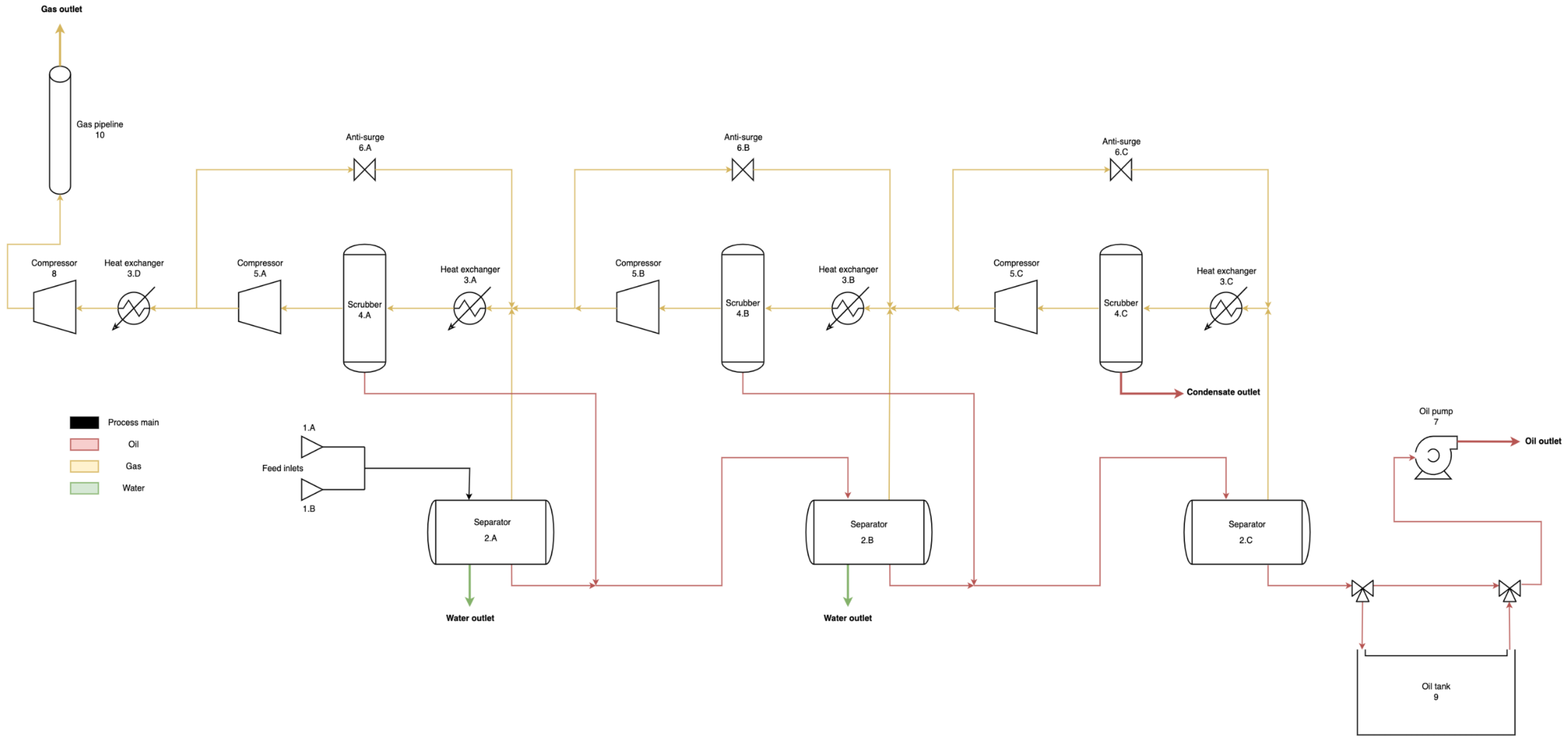

Figure A.1: A process flow diagram of the complete model

Appendix B

Table B.1: Produced petroleum composition.

Component	**Amount [mol - %]**	**Molecular weight [g/mol]**	**Specific gravity**	**T_c [K]**	**P_c [Pa]**
H_2O	3.83×10^{-1}	18.02	1.00	647.30	2.21×10^{7}
TEG	1.28×10^{-4}	150.18	1.13	770.00	3.33×10^{6}
Nitrogen	1.45×10^{-4}	28.01	0.28	126.19	3.40×10^{6}
CO_2	1.45×10^{-4}	44.01	0.84	304.13	7.38×10^{6}
Methane	2.91×10^{-1}	16.04	0.15	190.56	4.60×10^{6}
Ethane	7.27×10^{-2}	30.07	0.37	305.33	4.87×10^{6}
Propane	7.27×10^{-2}	44.10	0.52	369.85	4.25×10^{6}
N-Butane	5.82×10^{-2}	58.12	0.58	425.26	3.80×10^{6}
N-Pentane	4.36×10^{-2}	72.15	0.63	469.70	3.37×10^{6}
C6	1.45×10^{-2}	81.81	0.69	515.32	3.19×10^{6}
C7	2.91×10^{-4}	94.77	0.73	545.40	3.15×10^{6}
C8-C24	6.38×10^{-2}	179.98	0.83	685.71	2.03×10^{6}
C25-C47	2.55×10^{-5}	464.55	0.92	898.00	9.45×10^{5}
C48+	6.53×10^{-6}	829.22	0.96	1009.06	5.91×10^{5}

Appendix C

Code 1: Determining power consumption given available power.

```
import pandas as pd
from pandas import ExcelWriter
from openpyxl import load_workbook
import numpy as np

#Extracting wind power data from an Excel sheet
Pwind = pd.read_excel (r'C:\Users\AliQureshi\Documents\Masteroppgave\wind_data_extract.
    xlsx',sheet_name='Data')
Pavail = pd.DataFrame(Pwind).values

#Determining power consumption based on available power
Pconsump = []
save = 0

for x in Pavail:
    if max(P) <= x:
        Pconsump.append(max(P))
        save=x-max(P)+save
    elif x<= min(P):
        Pconsump.append(min(P))
        shortage=min(P)-x+shortage
    else:
        Pconsump.append(float(x))

#Saving power consumption values to a new Excel sheet
data = pd.DataFrame(Pconsump)
writer = pd.ExcelWriter(r'C:\Users\AliQureshi\Documents\Masteroppgave\
    wind_data_consumption.xlsx', engine='openpyxl')
writer.book = book
writer.sheets = dict((ws.title, ws) for ws in book.worksheets)
data.to_excel(writer, "Power_Consumption")
writer.save()
```

Appendix D

Code 2: Piecewise linear interpolation to determine production rate from power consumption.

```
from scipy import interpolate
import pandas as pd
from pandas import ExcelWriter
from openpyxl import load_workbook
import numpy as np

#Defining known data for production rate and power consumption
Q=[267.3,320.7,374.2,427.6,481.1,534.5,588,641.4]
P=[6.37,8.71,10.54,12.44,14.93,18.8,24.91,33.06]
print(max(P))

#Extracting available power data from an Excel sheet
Pw = pd.read_excel (r'C:\Users\AliQureshi\Documents\Masteroppgave\DATApython.xlsx',
    sheet_name='AvailablePower')
paw = pd.DataFrame(Pw).values

#Calculating required power consumption
Preq=[]
save=0
shortage=0
for x in paw:
    if max(P) <= x:
        Preq.append(max(P))
        save=x-max(P)+save
    elif x<= min(P) :
        Preq.append(min(P))
        shortage=min(P)-x+shortage
    else :
        Preq.append(float(x))

print("Available Power during a week at Gullfaks E126:",float(save),"MWh" )
print("Power shortage during a week at Gullfaks E126:",float(shortage),"MWh" )
print(Preq)

#Interpolating production rate from calculated power consumption values
f = interpolate.interp1d(P, Q)
Pnew = pd.read_excel (r'C:\Users\AliQureshi\Documents\Masteroppgave\DATApython.xlsx',
    sheet_name='RequiredPower')
Qnew = f(Preq)

#Extracting results to an Excel sheet
data = pd.DataFrame(Qnew, columns=["production x[10^3]"])
book = load_workbook(r'C:\Users\AliQureshi\Documents\Masteroppgave\DATApython.xlsx')
writer = pd.ExcelWriter(r'C:\Users\AliQureshi\Documents\Masteroppgave\DATApython.xlsx',
     engine='openpyxl')
writer.book = book
writer.sheets = dict((ws.title, ws) for ws in book.worksheets)
data.to_excel(writer, "PythonResults")
writer.save()
```

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