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Abstract

The concentration of greenhouse gases in the atmosphere is increasing rapidly because of burning fossil fuels. To reduce future emissions, the electrification of offshore oil and gas installations is discussed. The electrification of offshore oil and gas platforms is a method that has the possibility to safely reduce CO_2 emissions, that would have been emitted into the atmosphere if the traditional gas turbines are used to power the platforms. Different methods used to reduce CO_2 emissions have been a topic of discussion for many years. Leading the way for offshore electrification is the growing interest in green energy and the environment, along with the goal to reach net-zero by 2050.

Through the case study, it is shown that offshore electrification with power from shore of the Norwegian Continental Shelf is highly possible and necessary for Norway as a country, with respect to reducing CO_2 emissions and extending the lifetime of the petroleum industry, and strengthening Norwegian economy.

When replacing gas turbines and generators with power from shore to power offshore platforms, it is shown that full electrification has the potential to reduce 100% of the annual CO_2 emissions. Part electrification has the potential to reduce 51% of the emissions. Electrification of offshore platforms will contribute to a greener petroleum production compared to today’s production. As only 50% of the available petroleum resources on the Norwegian Continental Shelf remain, it is estimated that petroleum production can continue for many years. The decrease in future CO_2 emissions as a result of offshore electrification will secure Norwegian finance, but not yet alone it will secure many workers.

However, it needs to be mentioned that the offshore electrification aspect of the petroleum industry is promising when looking at both reducing climate change and the Norwegian economy. Without a doubt, more research is needed on the topic to be able to get a clear picture of the risks and costs compared with the positive aspect of reducing future CO_2 emissions by electrification of offshore platforms.

Acknowledgement

I would like to express my deep gratitude to my supervisor Homam Nikpey Somehsaraei for his excellent guidance, encouragement, and assistance throughout the work of this Master thesis. His guidance and knowledge have motivated me in every stage of the research. The thesis would not have been possible without his timely suggestions despite of his busy schedule.

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Nomenclature

GHG	Greenhouse gases
GT	Gas turbine
NOK	Norwegian Krones
PFS	Power From Shore
AC	Alternating Current
DC	Direct current
NCS	Norwegian Continental Shelf
FPSO	Floating Production, System and Offloading
PV	Photovolatic
kWh	Kilo Watt hours
GWh	Giga Watt hours
MWh	Mega Watt hours
CO_2 e	CO_2 equivalents
TWh	Tera Watt hours
HSSE	Health, Safety, Security and Environment
Tls	Tons of Liquid Steel
CAPEX	Capital Expenditures
Sm3	Standard Cubic Meters
GIS	Gas Insulated Switchgear
NO_X	Nitrogen Oxide
o. e.	Oil Equivalents
MNOK	Million Norwegian Krones
MSm3	Million Standard Cubic Meters

1 Introduction

Over the past decade, the climate has changed and the Earths surface temperatures have risen significantly. In the past, greenhouse gases, such as carbon dioxide, have been released into the air without any regard for possible consequences. Burning fossil fuels is the major cause of the increasing amount of CO_2 in the atmosphere [1]. Such increase in CO_2 concentration and the global mean temperature will result in an increase of the global sea level as a result of melting glaciers [2]. It is estimated that the global mean sea-level could rise with 0,75-0,80m for a 1,5-2,0°C temperature increase by 2100 [3].

The major greenhouse gases (GHGs) found in the atmosphere are carbon dioxide, methane, nitrous oxide, water vapor and chlorofluorocarbon [4]. GHGs result in an increase in the global temperature, as they are heat trapping. CO_2 is considered one of the major GHGs because it remains in the atmosphere for a longer period when compared to the other ones, even if some of them can trap more heat than CO_2. Because they don't stay in the atmosphere for a long time, the other GHGs do not contribute as much as CO_2 to global mean temperature increase [5].

The CO_2 levels in the atmosphere are at a record high, and the increase is happening rapidly. The concentration of CO_2 in the atmosphere was about 405,0 +/- 0.01 ppm in 2017, and reached reached 410 ppm in 2019, which shows a rapid increase [6, 7].

26% of the CO_2 emissions originate from the Worlds industry alone [8]. Most of these emissions are caused by combustion of natural gas on-site, that is used for power generation. Electrification of offshore oil and gas rigs may be a good opportunity to reduce future CO_2 emissions from the petroleum industry. This is a huge step towards the decarbonization of the oil and gas industry during the transition period as a rapid CO_2 emission has become more urgent than before, according to the recently released IEA report [9, 10].

Electrification is defined as the supply of energy an offshore installation either by power from shore or from power generated at the site i.e., from offshore wind. This installation can either be fully or partly electrified, depending on the energy demand [9, 11, 12]

With levels of greenhouse gas emissions and atmospheric concentration of CO_2 reaching these high levels in this short amount of time, something must be done relatively quickly [13].

1.1 Goals for the thesis

The following goals will be discussed and investigated throughout the thesis:

1. Investigate the background and principles for offshore electrification
2. Review ongoing electrification projects
3. To evaluate the risks and benefits of the implementation of offshore electrification systems.
4. To identify and discuss the possibilities given by part- and full electrification of the NCS.
5. Evaluate the possibilities that electrification could give with respect to CO_2 reduction from offshore oil and gas platforms via a case study and literature review.

1.2 Structure of thesis

Chapter 2 will provide the general information needed to understand the offshore electrification topic. In subchapter 2,1 a summary of atmospheric emission because of the petroleum industry is given. Subchapter 2,2 informs short about CO_2 as a greenhouse gas. Subchapter 2,3 is a description of the petroleum industry today. In subchapter 2,4 different methods to used power offshore installations is included, while subchapter 2,5 reviews power from shore and on-site electricity generation. Subchapter 2,6 is a brief introduction to the Norwegian power situation, and subchapter 2,7 introduce clean energy alternatives. A risk analysis is provided in subchapter 2,8, and a cost analysis is provided in subchapter 2,9. A review of offshore electrification is given in 2,10, while a brief review of ongoing electrification project is given in subchapter 2,11.

Chapter 3 describe the case study and site characterization, while chapter 4 is the case study including results and discussion of CO_2 emissions, costs and potentials for electrification on the NCS.

Chapter 5 concludes the results from chapter 4 together with the background information given in chapter 2.

The appendix provides the calculations used in chapter 4.

2 General Background

To fully understand the topic some general background about the petroleum industry, offshore electrification, the Norwegian power situation, and clean energy sources is given in the following chapter.

2.1 Emissions from the petroleum industry

Emissions from the petroleum industry is one of the biggest contributors to emissions of greenhouse gases [14]. The combustion of natural gas and diesel in turbines, motors and burners are the main contributors to atmospheric emissions in the petroleum industry. Beside this there are also emissions due to gas flaring, and a small number of emissions due to well testing [15]. The percentages of emissions due to the different processes is shown in Figure 1.

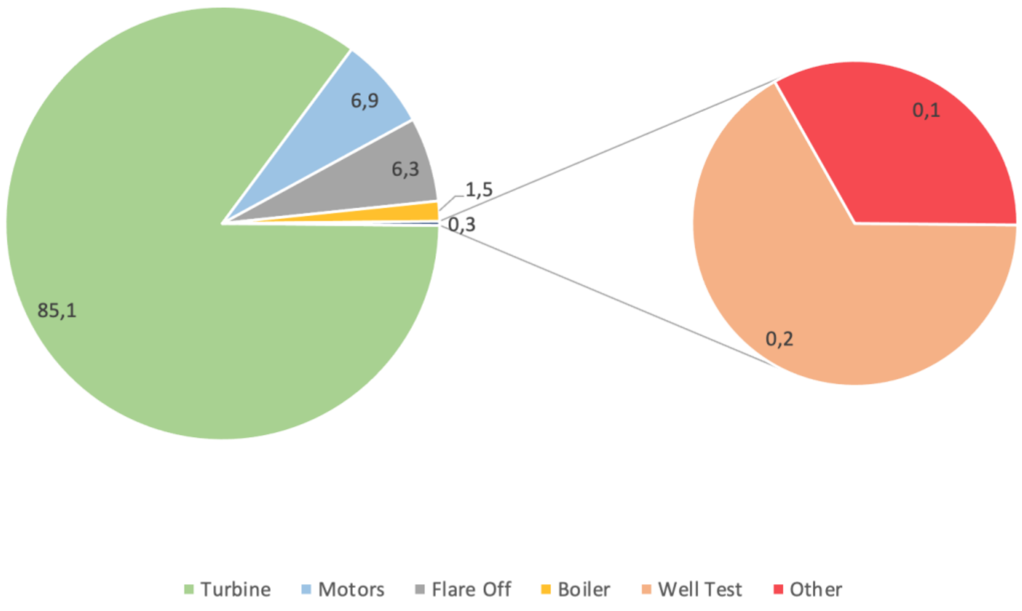

Figure 1: Emissions in the petroleum industry, shown in percentages [16].

In Norway, the oil and gas sector are considered the second largest source of greenhouse gas emissions. The oil and gas industry are accountable for as much as 27% of the total emissions in Norway, where gas turbines and flare off is the main contributors. As for 2020, a total amount of 13.2 million tons of CO_2 – equivalents are released into the atmosphere because of the oil and gas industry in Norway. A total amount of 71.74% of these emissions are due to electricity generation and mechanical work for injection from gas turbines on the offshore installation [17, 18].

Gas turbines can be run by two configurations, either by a steam turbine power plant or a combined cycle power plant, with efficiencies of 35% and 65.3% respectively. This is resulting in 65-34.7% of the total energy consumption getting wasted and released into the atmosphere [19].

As a lot of electrification projects is happening on already existing platforms, modification on the platforms is needed [16, 20]. When modifying offshore platforms, huge amounts of steel is needed. For example, aluminum is used in the offshore industry as it does not corrode and require little maintenance, alongside with the light weight compared to other steel types. This make aluminum preferable [21]. When producing one ton of aluminum a total of 11,5 tons of CO_2 is produced [22]. In the offshore industry, carbon steel are also used [23]. On an average, it is emitted 1,85 tons of CO_2 per ton of produced steel [24].

2.2 Properties of CO_2 as a greenhouse gas

Carbon dioxide is a gas complex molecule with a variety of properties, consisting of one carbon molecule connected with two oxygen molecules by double bonds. As mentioned, the concentration of CO_2 in the atmosphere in 2017 were about 405 which increased to 410 ppm in 2019 [6, 7] . Such rapid increases will have a huge impact on the environment. Alongside with the increasing temperature, an increase in atmospheric CO_2 will contributes to the life cycle of plants and animals [25, 26]. Researchers have discovered a correlation between increased concentration of atmospheric CO_2 and increase in the photosynthetic rates [27, 28]. As concentration of CO_2 in the atmosphere increases, the global mean temperature increases. This will lead to melding of ice sheets and glaciers, which will result in a rise in the global sea-levels all around the World [29, 30]. The correlation between atmospheric CO_2 concentration and average global temperature from 1880 to 2010 is shown in Figure 2. The trends in Figure 2 show that as the CO_2 concentration in the atmosphere increases, and so the global average temperature [31].

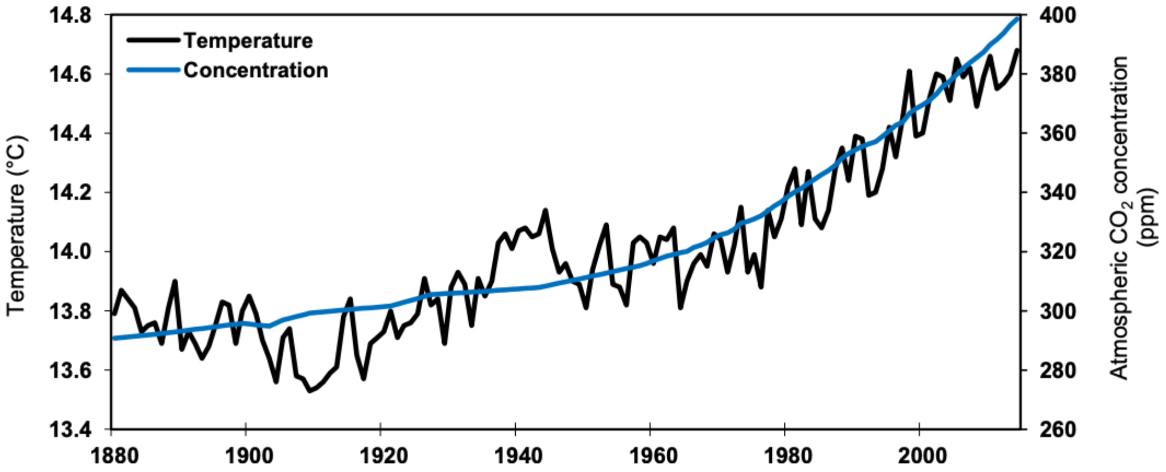

Figure 2: The correlation between atmospheric concentration of CO_2 and average global temperature [31].

2.3 The petroleum industry in Norway today

The petroleum industry in Norway have had a huge impact on the economic growth since the mid- 1960s. The economic growth happening due to oil and gas have had a great deal for the financing of the Norwegian welfare society [32]. Since the beginning, the petroleum industry have provided Norway with 15 700 billions of Norwegian krones (NOK), and is currently considered being the most important industry in the country [33].

Petroleum production in Norway has had a rapid increase since the 1970s. Figure 3 represent the production of oil, gas condensate and gas in Norway from 1970 to 2020. Since the 2000s the total production of petroleum has been relatively stable around 225 millions of Sm3 o.e. (standard m2 oil equivalents) [34]. The unit Sm3 o.e. indicate the energy content in all types of petroleum using one unit [35].

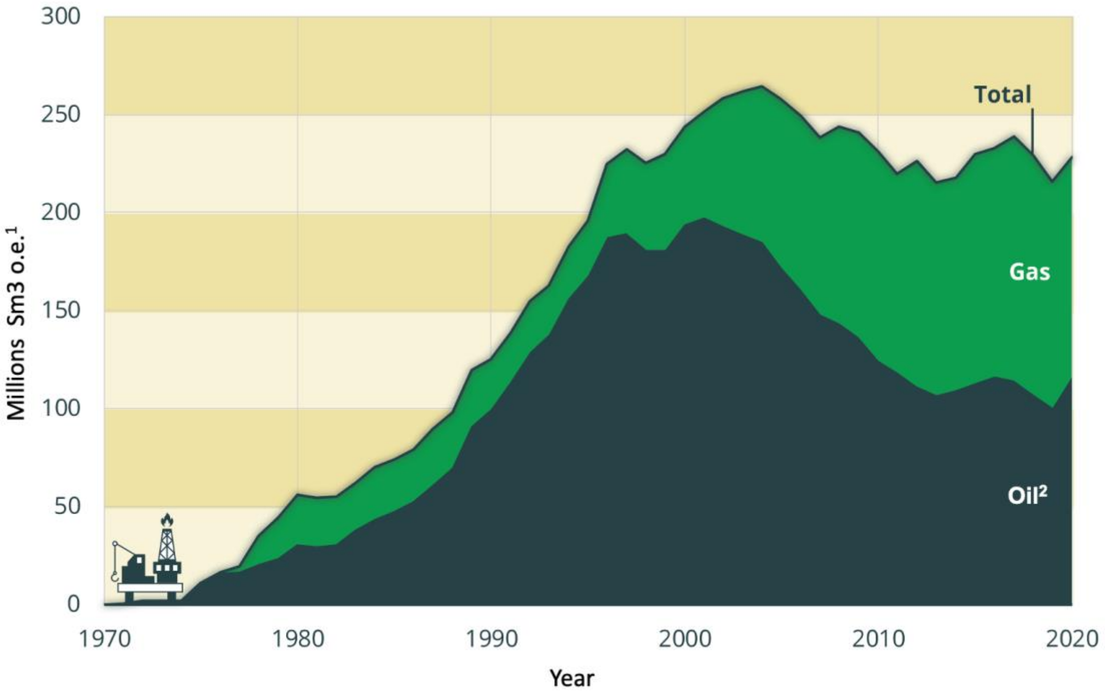

Figure 3: Petroleum production in Norway from 1970 to 2020 in millions Sm3 o.e. [34].

The Norwegian petroleum industry is highly important for the labor market. In 2019 there were about 200 000 people working either directly or indirectly with the oil and gas industry. These 200 000 people account for 3,74% of the entire population in Norway working toward the petroleum industry, one way or another. During 1980 to 2020 a steady increase in people working towards the oil and gas sector has happened [36].

The activity on the Norwegian Continental Shelf will continue for years and will affect the finance of the country. This because there are still a lot of remaining resources found in the oil and gas reservoirs [32]. Only 50% of the available resources have been produced and sold, meaning that there are equally as much left. This indicates petroleum production for 50 more years [37].

The leading oil and gas companies in Norway, are leading the way towards a more environmentally friendly petroleum production. By doing this they keep the cash flowing and keeping a large part of the Norwegian population working in the industry [38 – 40]. The main goal of Equinor is to be a leading company towards the way to reach net-zero emissions by

2050. One of the strategies used to meet this goal is to optimize the oil and gas production. A way towards this is to electrify offshore assets on the Norwegian Continental Shelf, mainly with power from shore [41].

2.4 How to drive platforms

As of today, offshore oil and gas platforms are most commonly driven either by the known gas turbine, part-electrification, or full electrification systems [12, 42]. These three methods will be described in the following sections.

2.4.1 Gas Turbine Cycles

The most common method of powering offshore installations is through the well-known gas turbine cycle. The electricity generated by the gas turbine can meet the electricity demand, while the process heat is provided by the concept of a heat recovery unit, which utilizes the thermal energy available in the exhaust gas of the gas turbine [42, 43]. A schematic diagram of a gas turbine on two installations, A and B, is shown in Figure 4.

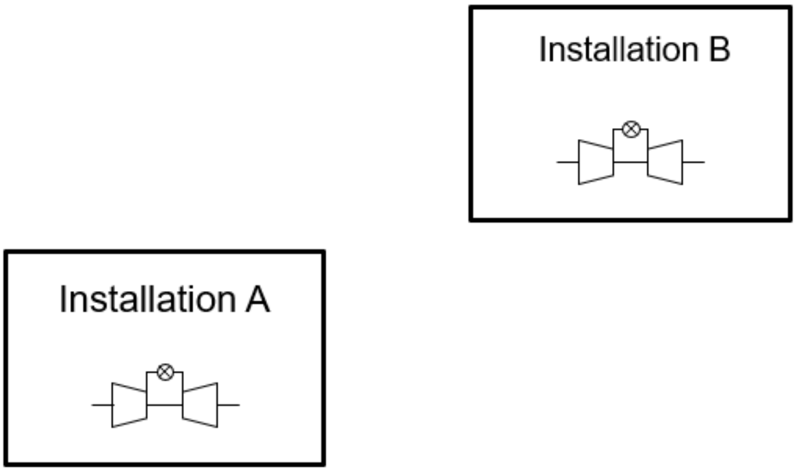

Figure 4: Diagram of a basic gas turbine cycle on two offshore installations, A and B. Modified from [42].

A second method is to add a steam bottoming cycle. In a once-through heat recovery steam generator, steam is lifted and then expanded in a steam turbine. The present waste heat recovery unit receive process heat from the gas turbines exhaust gas, while the downstream bottoming cycle makes use of the remaining thermal power in the gas. The usage of gas turbine cycles has the potential to reduce CO_2 emissions by 20 – 25% when compared to a simple gas turbine [43, 44]. Figure 5 show a schematic diagram of a typical gas turbine cycle system.

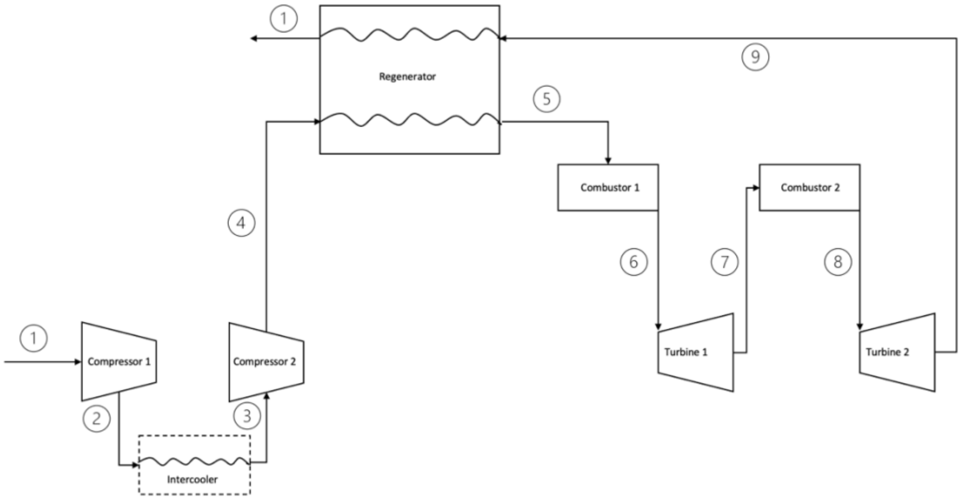

Figure 5: Diagram of a typical gas turbine cycle system [34].

2.4.2 Full Electrification

The second concept involves the full electrification of the installation. Most commonly the power needed is provided by the onshore grid. The use of shore power (PFS) inevitably reduces the amount of gas burned locally. Therefore, a large amount of gas needs to be compressed and output [42, 43]. Full electrification has the potential to reduce as much as 56% of the CO_2 emissions compared to on site power generation wit gas turbines [12].

Other methods for providing power to a fully electrified installation may be offshore wind, hydropower and solar power produced near the installation [45, 46]. A schematic diagram of full electrification on two installations, where installation A gets power provided from shore, and installation B gets power from installation A is shown in Figure 6 [42].

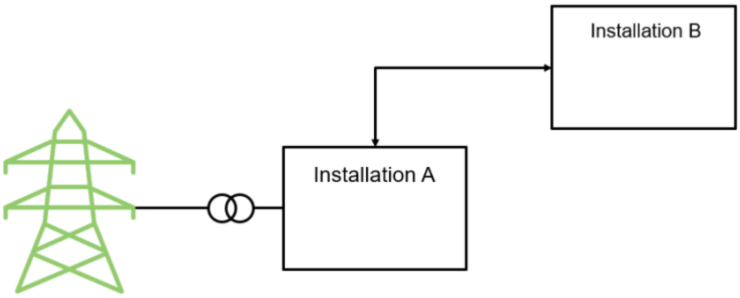

Figure 6: Diagram of full electrification, power from shore. Modified from [42].

2.4.3 Part Electrification

This concept is a hybrid of the first two. Heat and part of the electricity are produced locally using gas turbine and waste heat recovery units, while remaining electricity needs are provided by PFS. Various offshore platforms are considered to be connected by AC (Alternating Current) cables. The main task of the GT is to meet the heat demands, so that the GTs are located on the platforms that require process heat (i.e., Edvard Grieg and Johan Sverdrup). The load at which the GT is expected to operate is the result of a constrained optimization process: optimizing the ratio between offshore and shore power supply to minimize CO_2 emissions. Figure 7 shows a schematic diagram of the concept [42]. Part electrification with on-site power generation and PFS has the potential to reduce CO_2 emissions with 48%, when compared to only using gas turbines [12].

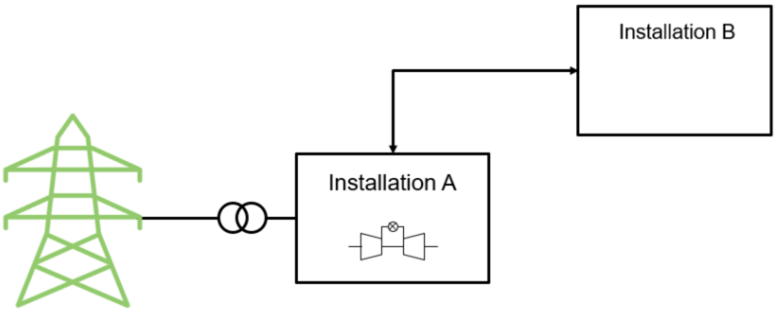

Figure 7: Schematic diagram of partial electrification. Modified from Riboldi et al., (2019) [42].

To partly electrify offshore installations different hybrid combinations can be used. The combination of gas turbines, waste heat recovery units and power from shore is obtaining power from shore, while the gas turbine is running to meet the process heat requirement. In addition, the gas turbine will produce some power, decreasing the need for power from the shore. This method can be adjusted with respect to the power from shore emission factor. The emission factor is defined as a value that can relate the quantity of emitted pollutant with the source activity [47]. For example, when the CO_2 emission factor is high, it may be more convenient to produce as much as the power locally offshore. For years with low CO_2 emission factor, it may be more convenient to meet the power demands with PFS [43].

Another commonly used method for partly electrification is to have a hybrid version combining power from shore and a waste hear recovery unit. By this method, the power demand is met by power from shore. In addition to this there is a gas fired system that provides heat by exploiting the existing waste heat recovery unit [43].

2.5 Offshore Power Alternatives

Production of electricity, direct operation and heat production is the main processes that uses power on offshore installations [16]. This section will review possibilities for power from shore and power generated at the installation.

2.5.1 Power from shore

Power from shore is considered being one of the measures that results in the highest reduction of greenhouse gases from the oil and gas industry [16, 30]. To provide oil and gas platforms with power from shore involves the power being lead in cables from the land-based power grid. This has the potential to reduce emission as the power isn't provided by natural gas or diesel anymore [30]. In Norway, 91,8% of electricity is produced from hydro power [48].

Power from shore can be transferred to the offshore installation either via AC or DC (direct current). To transport a large amount of power over a large distance, which is most commonly for offshore electrification, DC is the best option. A problem with DC transmission is that the power needs to be transferred to DC on shore, as the power grid onshore and the installation uses DC, and then it has to be transferred back to AC again as that is what is used on offshore installations. The equipment needed to transfer DC to AC is big and heavy, and have high costs [16, 49 – 51].

If one instead uses AC, the total costs is usually lower because there is no power transformation needed. Thus, less, and smaller equipment is needed, compared to the DC. The major drawback for AC is the limitations in the distance it can be delivered [16, 49 – 52]. However, it shows that low frequency transmission, reactive compensation and serial compensation might be the solution to supply AC over larger distances than done these days. The usage of low frequency transmission has made it possible to transfer AC over longer distances than before. The Jansz-lo- field outside of Australia, is planned to use AC power from shore of a distance of bout 200 km [16, 52].

Figure 8 show different power from shore electrified offshore installations as a function of power supply and distance from shore. AC and DC transmission is also considered in Figure 8. Serial compensation, reactive compensation and low frequency transmission give possibilities to provide AC power from shore at greater lengths and power supply than without it. The Figure also show that DC transmission has the possibility to provide more power at greater distances than all of the AC alternatives [16].

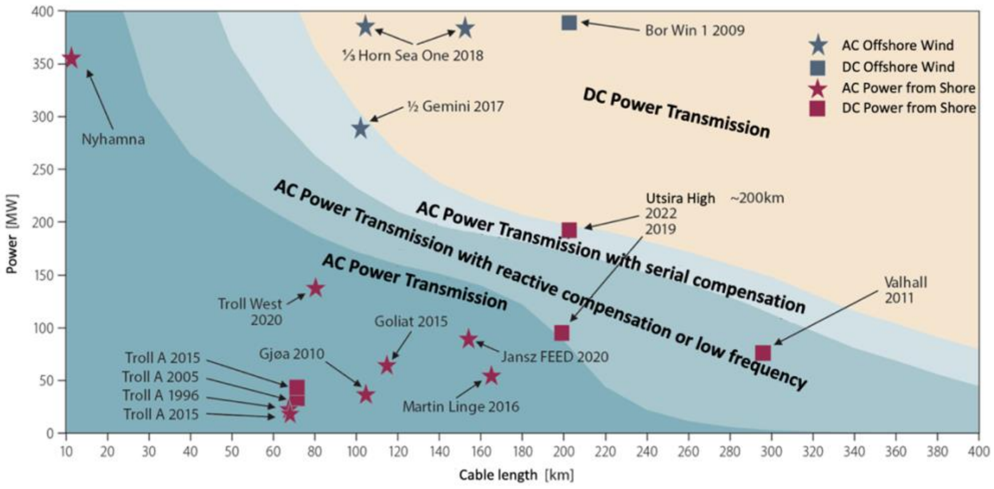

Figure 8: Different offshore installations as a function of power supply and cable length [16].

To get power from shore up and running, the offshore installation needs a large amount of new equipment installed. This equipment tends to take a lot of space and high cost; thus, it can be a challenging part of the transition to power from shore [16].

Another point affecting both the scope of work and the total cost is the distance from the installation to the shore. This can be a problem for already existing offshore installations on the NCS (Norwegian Continental Shelf) that has the potential to be electrified, as they may be located at greater distances from the shore [16]. Figure 9 shows a map of the NCS illustration the distances from shore.

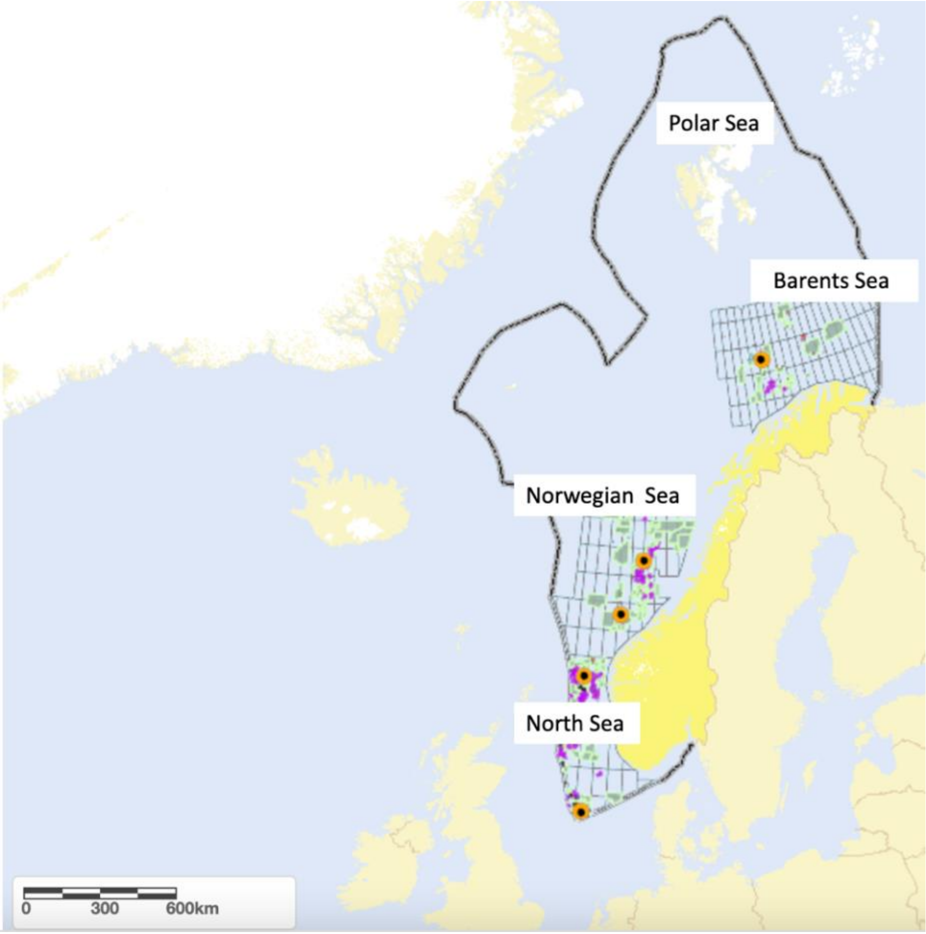

Figure 9: Overview of the Norwegian Continental Shelf, with legend [53].

The kind of installation to be electrified will also affect the costs and scope of work when looking at the electrification of offshore oil and gas platforms. The cables that are connected to a floater needs to be dynamic, i.e., they must tolerate the movement of the platform. This makes the cable design more complex. For FPSO (floating production, system, and offloading) is rotating around its own axis. Power from shore to these types of rigs require the power to be transmitted through the turntable. Without the turntable the cable would be twisted and destroyed because of the rig's movement. As for today there are no FPOS getting power from shore. An example of a FPSO is the Skarv vessel. The vessel is located, and anchored to the seabed in the Skarv field, in the northern parts of the Norwegian Sea [16, 54, 55]. The vessel Skarv FPSO is owned by Aker BP and have the capacity to produce 85 000 barrels of oil per day and 775 million standard cubic feet per day of gas. The storage capacity of the vessel is 875 000 barrels [54, 55]. The Skarv vessel is shown in Figure 10.

Figure 10: Aker BP's FPSO vessel Skarv [16].

2.5.2 On-site power generation

A possibility for on-site power generation may be offshore floating wind turbines, located near the offshore installation that is supposed to be electrified. An example of this is

Equinor's project Hywind Tampen as well as Worley and Hexicons TwinWind project , which will be further described in section 2.7.1 [45, 56 – 58].

Offshore solar power generation is another alternative to on-site power generation [59, 60] . Benefits of establishing offshore plants include higher solar panel efficiency due to the cooler environment, PV (Photovoltaic) cell cleaning, and reduced evaporation losses. Offshore solar PV is a relatively new and expanding area with a lot of room for advancement. The structure of the solar panel is the key issue in offshore solar applications. The efficiency of offshore solar power ranges from 10-20% [59].

Among large-scale natural gas-fired power plants, the combined cycle (gas and steam) is currently the most competitive. Because of the high efficiency, low investment costs, improved operating flexibility, short installation time, and low environmental impact, the combined cycle is very attractive for power generation and for cogeneration of heat and power, when compared to other fuel-based technologies. The low CO_2 emissions in gas-fired power plants is because of the high hydrogen/carbon ratio of natural gas and the high cycle efficiency [61 – 63]. The efficiency of combined cycle power plants can be as high as 60% [19].

Solar energy is a highly valuable renewable energy resource, and solar evaporation technology is one technique to capture it efficiently. Solar energy could generate heat, steam, and electricity during the evaporation process. For solar steam and energy generation, a low-cost, reusable, and efficient evaporation system has been created. The evaporation efficiency can be as high as 85% [64, 65].

2.6 The Norwegian power grid and power situation

The electrification of offshore platforms in the coming years will have an impact on the Norwegian power grid and power market. Electrification of offshore installations requires large amounts of power, and this will affect the Nordic power flow and the power market [24].

A total of 91,8% of all electricity in Norway is generated from hydro power plants. Wind power and thermal power accounts for 6,4% and 1,7% of the power generation, respectively [48]. This is shown in Figure 11.

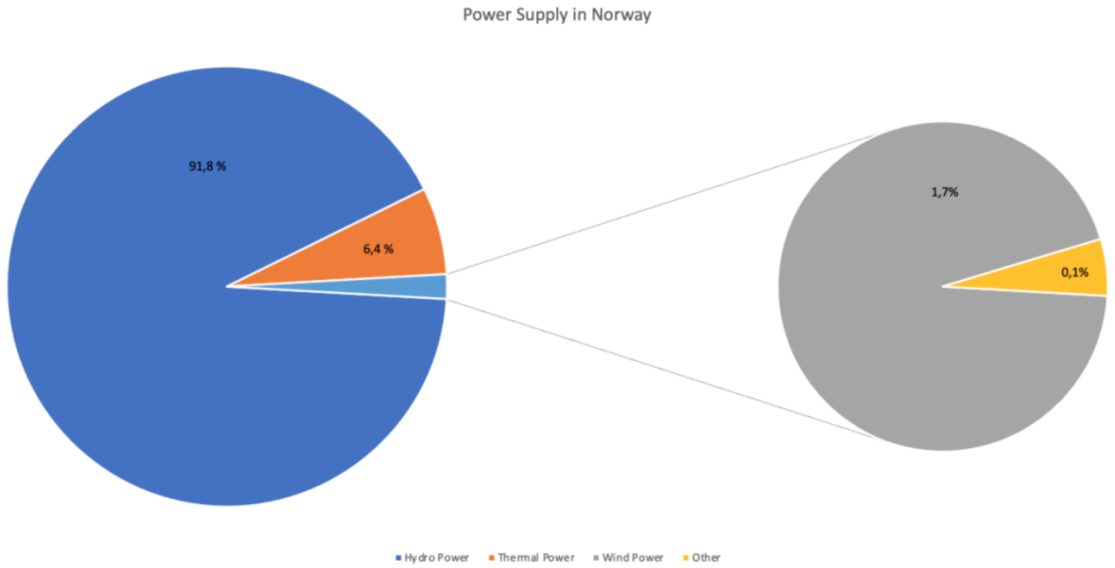

Figure 11: Overview of the electricity sources in Norway [48].

2.6.1 The Norwegian power grid

To keep the power grid working, a balance between power consumption and production is needed. As Norway is exposed to the weather changes, the power situation will vary along with it, across the different regions. There is no possibility to equalize the differences in the power capacity. The solution to this is to divide the regions into five different price range areas, depending on the capacity [16, 66 – 68]. Figure 12 gives visual overview showing the different price ranges areas (N01 – N05).

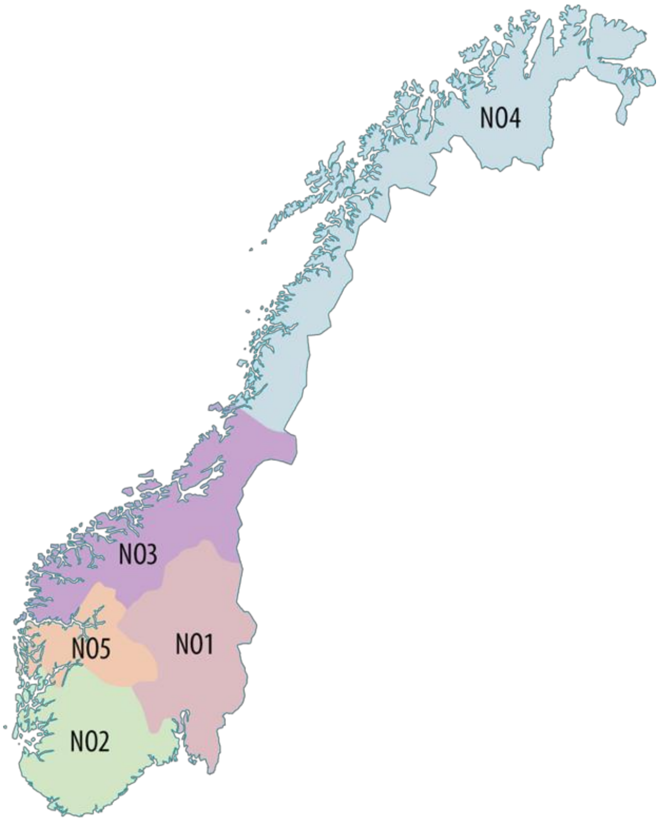

Figure 12: Overview of the price areas for power in Norway[16].

Huge parts of the power production are happening in the Western part of Norway and in Norland. If the yearly production is stable and normal, there is a need to transport some of the power produced in these areas to the eastern parts of Norway, where less power is produced. In the Northern parts of Norway there is a high-power production in Nordland and Troms, but less in Finnmark. Thus, power is transported from Nordland and Troms, to meet the power demand in Finnmark. Power is always transported from the producing site to the areas with the highest power demand [16].

2.6.2 Power balance

The north is a common power market for Norway, Sweden, Finland, Denmark, Estonia, Latvia, and Lithuania. These countries buy and sell power to each other on a daily basis. The prices are regulated by power availability and demand and fluctuates hourly. The countries are divided into different price range areas, e.g. NO03 [66]. In Figure 13 the effect flow from these counties is shown. Figure 13 only represent the 19th of April 2022, at 13:00.

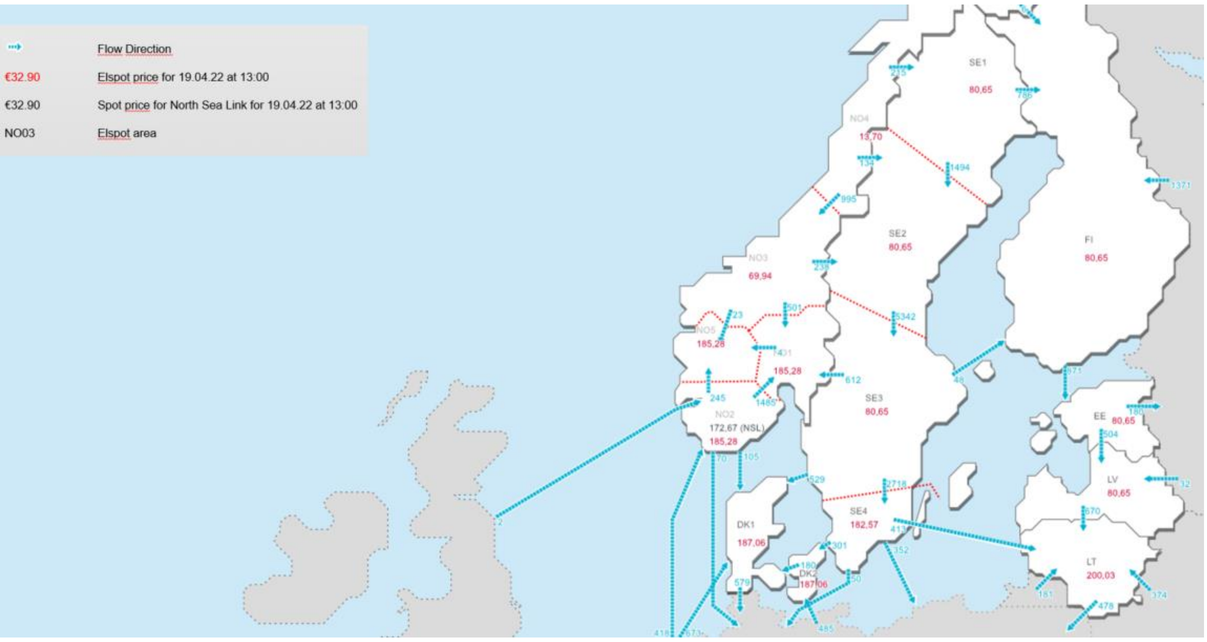

Figure 13 : Overview of effect and price range areas in the different Nordic countries [66].

Figure 13 show that all the countries are depending on each other. Changes in demand and/or supply in one country will most likely affect all the countries shown. Because future electrification project will need a large amount of power supplied, it is important to have a look at the mechanisms and collaboration in the electricity market [66].

As for the North, West and middle parts of Norway, the major consumer of power in the coming years is the electrification of offshore oil and gas installations. However, there is not enough power production in these areas to meet the power demands in Norway. Statnett is working with comprehensive measures to be able to meet the expected power demand in the following years [60]. An overview of the power production and consumption in Norway is provided in Figure 14.

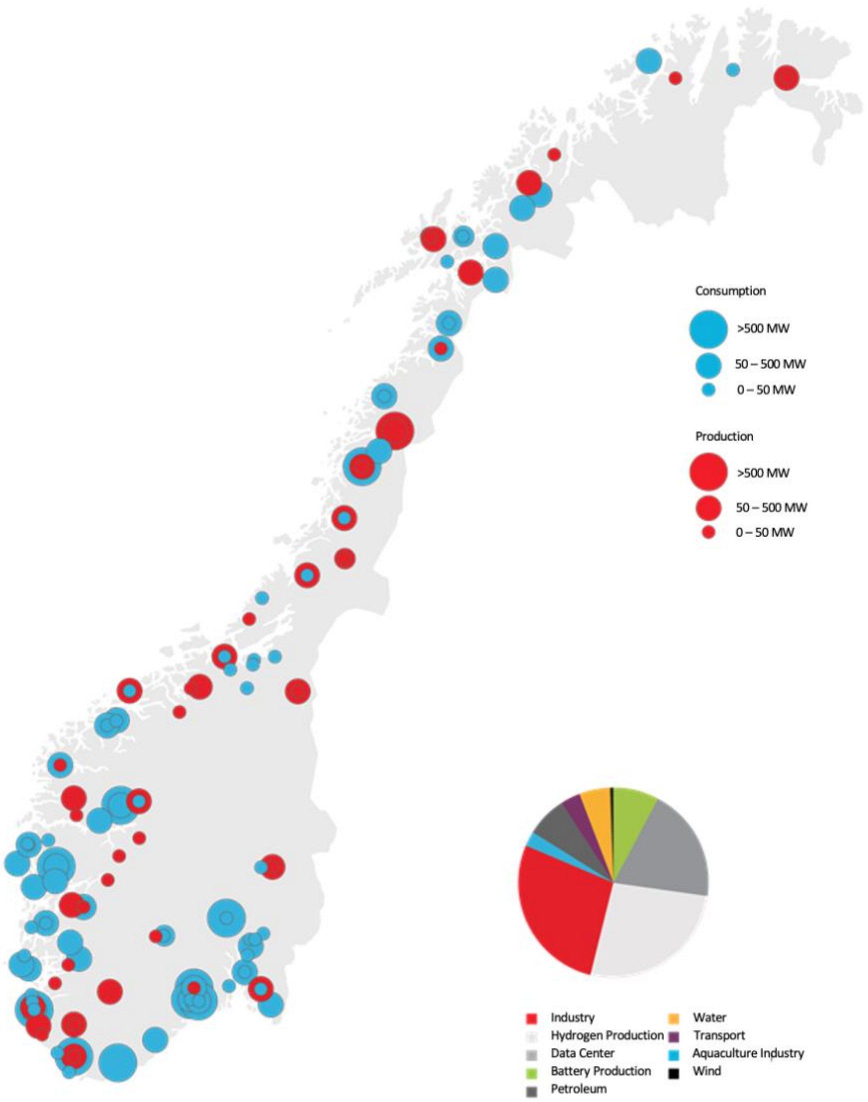

Figure 14: Overview of the power production and consumption in Norway as of 2018-2021 [69].

Figure 14 illustrate that the Southwestern part of Norway consumes more power than produced. This is also valid for the Southeastern parts. The pie diagram in Figure 14 illustrate that the major consumers of power is industries, hydrogen production and data centers [69].

When looking at the import, export, and net exchange of power from 2011 to 2021, the net exchange of power is positive for all years, with an exception of 2019, where the net exchange of power were zero [70].

2.6.3 Power prices

As mentioned, Norway is a part of the Nordic power market. The connection to other European countries strengthens the supply capacity, reducing the overall costs in the power supply and facilitation of more renewable power production. The power price in Norway is continuously affected by the supply and demand for power in the Nordic power market [66].

As shown in Figure 12 Norway is divided into five different price range areas, i.e. NO01, NO02, NO03, NO04 and NO05, based on how much capacity there is in these areas [66, 67]. When there is more electricity produced than consumed in one area, the price will be lower. Another factor controlling the price is the limited capacity to electricity transport [67].

The electricity price is also affected by the seasons such as the weather, the hydrological balance, climate change, politics, coal and gas prices, production capacity, taxes and the European quota price for CO_2 , in short and long term [67].

Data collected from Statistics Norway (Statistisk Sentralbyrå) show an increasing trend in the power prices. From 2012 to 2017 the power price in Norway was relatively stable at 30 to 35 Norwegian øre/kWh. A slightly increase to approximately 55 Norwegian øre/kWh in 2018 and 2019, before a rapid decrease in 2020. During 2021 the price increases from 22,2 Norwegian øre/kWh to 108,1 Norwegian øre/kWh [71]. These numbers are visualized in Figure 15.

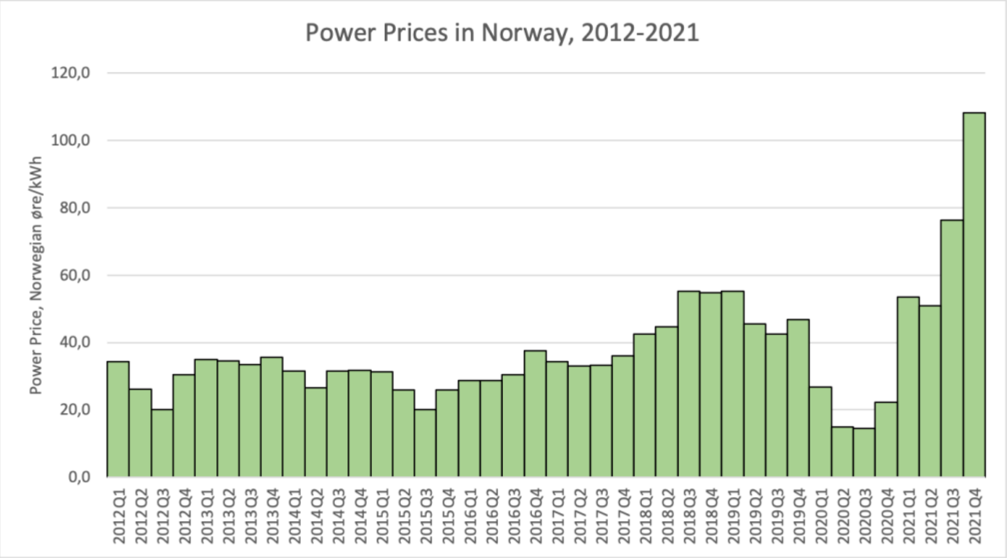

Figure 15: Power prices in Norway from 2012 to 2021 in Norwegian øre/kWh [71].

2.7 Clean energy production

The power business contributes to a wide range of issues concerning environmental preservation. It should be considered not only in terms of its impact on nature, but also in terms of implications for human life quality [72].

If the electrification of offshore installations is implemented in large extents in the offshore industry, more electricity needs to be generated [73]. To avoid environmental concerns, electric energy must therefore be produced in power plants using alternative sources of energy. In this section energy sources that are considered clean will be discussed, this includes wind, hydro, solar, nuclear and geothermal power plants [72]. According to Statnett, solar power and wind power seem to be the best options for Norway [74].

2.7.1 Wind Power Plants

Wind power is an attractive alternative for a renewable source of energy, and have had a huge development in its technology [75 – 77]. It is estimated that wind power will provide 15-18% of the global electricity by 2050. Looking back to 2017, it is reported that the power provided from wind is about 50GWh, which is approximately 11% [75, 78]. A study done by Wang and Sun, shows that wind power produces the least CO_2 emissions, when compared to both fossil fuels and other renewable energy sources [79].

Wind power is based on the fluctuations of the wind, and is transforming the kinetic energy from wind into electricity [72]. The blades on the wind turbines captures the wind, and transforms it into rotating mechanical power [80] A lot of different factors will affect the efficiency of the wind power plants, such as wind direction, wind speed, temperature, pressure, humidity etc. [75, 81].

The technology is flexible, and wind turbines can be placed at various locations with different geographies all around the world, both on- and offshore [82, 83]. The most recent development regarding wind power energy is the offshore wind power plants [84]. This may be due to the fact that offshore wind farm isn’t visible for the majority of people [82].

The Norwegian coastline is about 2500 km long with fjords, islands, and mountains. The climate at the western parts of Norway is dominated by westerly winds, which indicate a large potential for wind power [85]. As of 2022, there are currently 1300 wind turbines distributed in 63 different facilities running in Norway. Together they have a yearly production of about 15,3 TWh. The wind turbines used for this calculation are both offshore and onshore [83].

The wind map of Norway in Figure 16, show that there are strong winds ranging from ~ 8.0 to 10.5 m/s along the coast. On shore the wind range is <8.0 m/s [86].

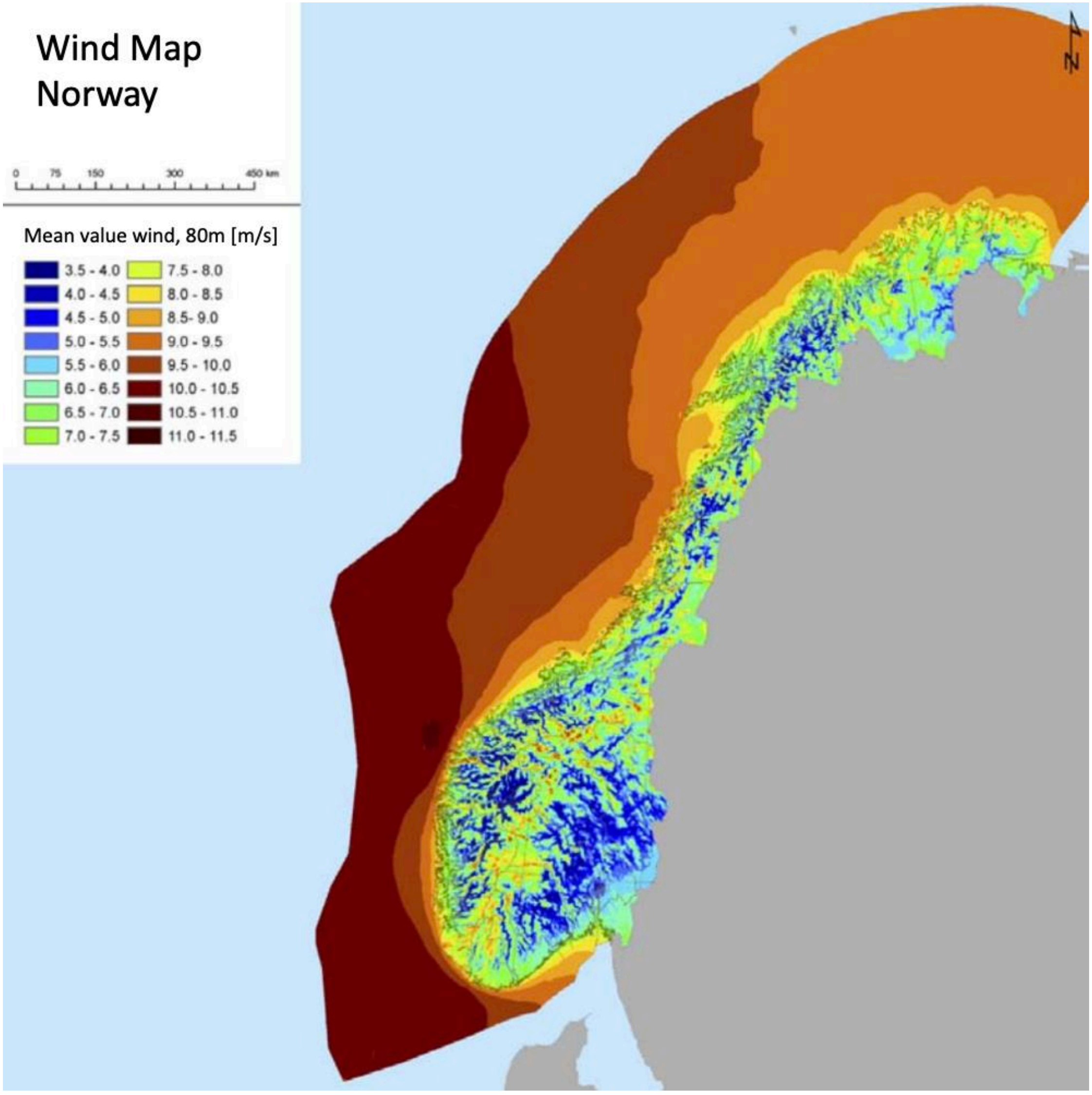

Figure 16: Map showing the average wind speed at an altitude of 80m in Norway [86].

When comparing the onshore and the offshore wind power plants, offshore power plants have the highest potential to generate electricity, as there are better wind conditions offshore. This is the main reason why offshore wind power plants are preferred, despite the higher costs due to transmission and the higher total CO_2 emissions for offshore power plants compared to onshore plants [79].

Estimated CO_2 emissions of offshore and onshore wind power plants is shown in Figure 17. The Figure show that offshore wind power plants emits 1,02 g/kWh more CO_2 than the onshore wind power plants [79].

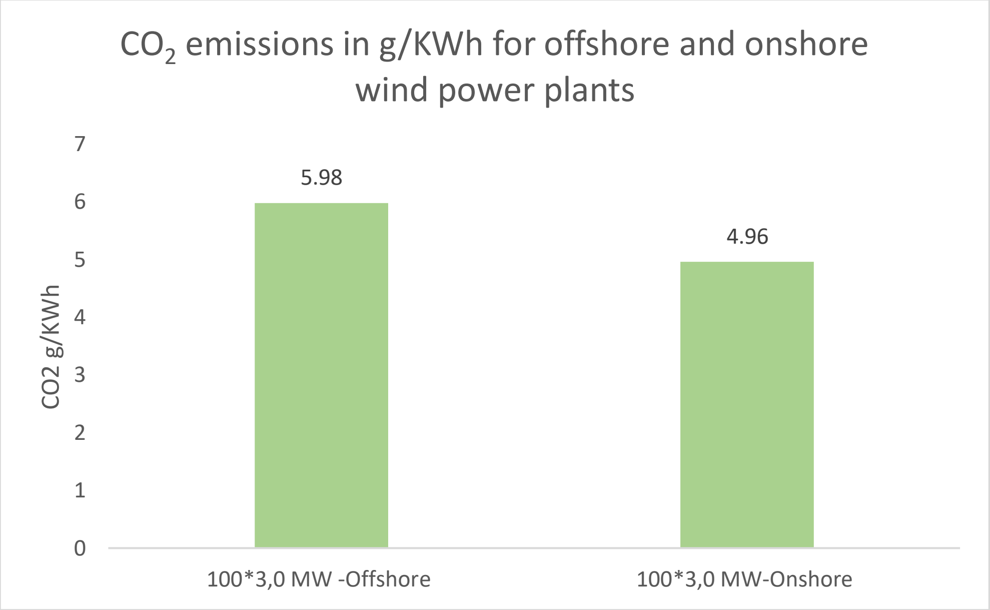

Figure 17: CO_2 emissions on offshore and onshore power plant in g/KWh [79].

Equinor's project Hywind Tampen is an offshore floating wind farm located in the North Sea. The purpose of the project is to serve electricity to the nearby offshore fields, Snorre and Gullfaks. The wind farm, consisting of 11 wind turbines, will have a combined capacity of 88MWh. This will provide about 35% of the energy demanded for Snorre A and B, and Gullfaks A, B, and C platforms [45, 56]. A visual overview of the Hywind Tampen project is shown in Figure 18.

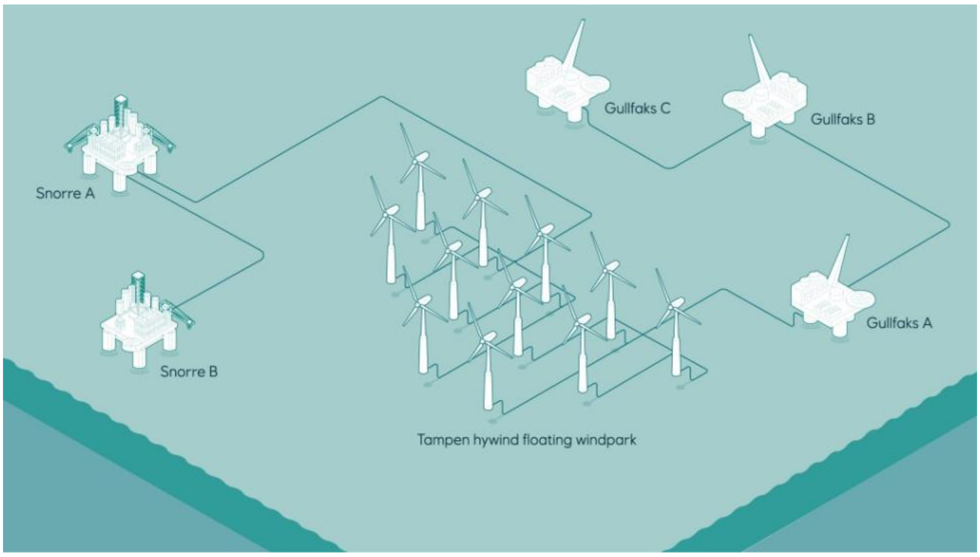

Figure 18: Overview of the Hywind Tampen floating wind park and surrounding platforms [56].

Twin wind is Hexcion and Worley’s floating wind foundation technology. The main elements are two wind turbines and weathervanes. The elements are located around a single mooring point. By using this technology, there is a possibility to place several wind turbines in the chosen area [57]. Hexicons TwinWind model is shown in Figure 19.

Figure 19: Hecixon's model of the TwinWind project [57].

2.7.2 Solar power plants

Solar electricity plants harvest photo voltaic energy from the sun. The electrical energy is received through a direct technique by the means of the usage of PV or via an indirect one by means of collection heat and then transforming it into electrical energy [72].

In Norway, there is 700-1000 kWh/m2 solar radiation on average. The highest potential for solar power is in the Southern and Eastern part of Norway. When comparing this to other countries in Europe, it is equal to the Central parts of Germany, where solar power is widely used. This indicates that there are potentials for solar power in Norway [87 – 89].

The solar radiation in Norway varies a lot with the seasons, and the highest solar radiation takes place during the summer, and the solar radiation is at its lowest during the winter. A visualization of this is provided in Figure 20. The relatively cold temperature in Norway is an advantage when looking at solar cells, as they have a higher efficiency at a colder temperature range [87, 89].

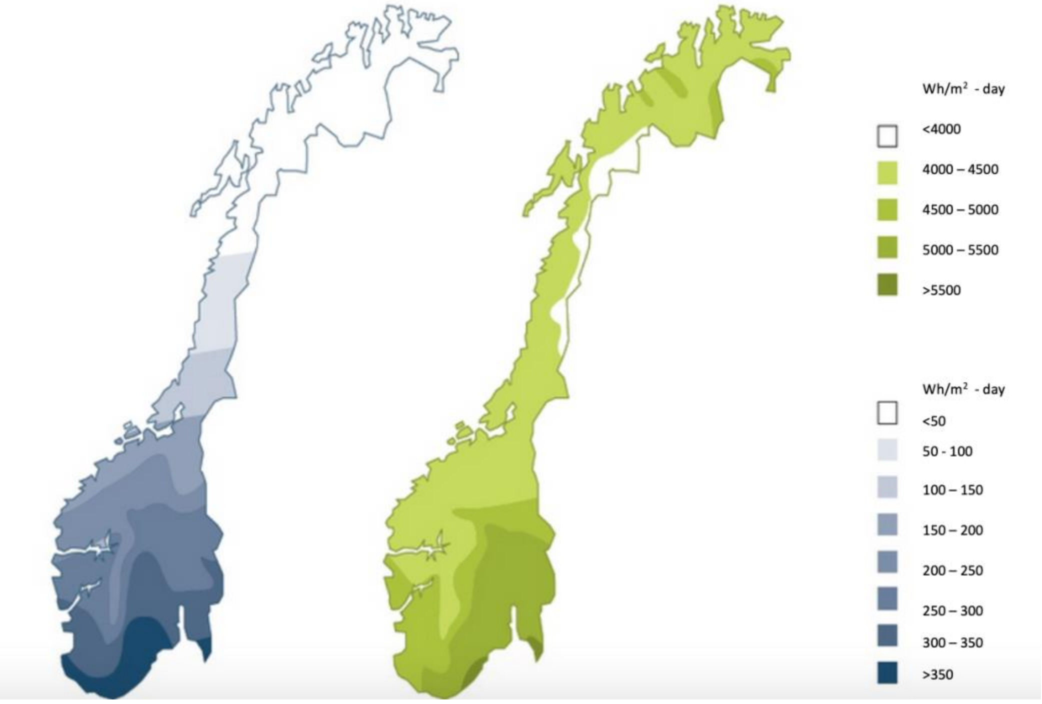

Figure 20: Solar radiation in Norway for January and July in Wh/m2 per day [87, 88].

Advantages are found with power generation from solar energy is that it requires low maintenance and is a free energy source. The maintenance and operations costs are low, thus is considered a truly clean energy source [90, 91].

The main disadvantages it the unit costs of PV cells and the cost of solar electricity is quite high as for now. It is predicted that these costs will increase alongside with the maturity of the solar cell technology. Other disadvantages is that it requires a large installation area and it is dependent on geographical conditions (solar radiation) [90, 91].

Different studies done by National Renewable Energy Laboratory and Nature Energy show that during the 25 year lifespan, solar power emits between 40-21g CO_2e (CO_2 equivalents)/kWh [92].

A new and upcoming technology for solar power is the floating solar power plants [93, 94]. A study done on large PV power plants on shore, indicates that there are possibilities for heat islanding effect in modern cities, which is harmful for human beings [95, 96]. Due to this, it is proposed that floating solar power plants is one of the best alternatives when it comes to solar power plants [95].

2.7.3 Hydropower Plants

Hydro power plants use the kinetic energy of flowing water, or the potential energy of water stored in dams in the Earths gravitational field to generate electricity. The use of flowing water to drive turbines have the advantages as it does not affect habitation of people, and it has almost no environmental impacts compared to the dams [72, 97]. Globally, hydropower is considered the most important form of renewable energy, providing 19% of the planets electricity demand [97].

There are a total of 1893 hydropower plants spread all over Norway. Together, these plants accounts for 96% of all hydropower production, making Norway's power production approximately 100 percent renewable. The 10 largest hydropower plants in Norway have a yearly production of 25 018 GWh. This result in an daily average power production of approximately 69 GWh/day [98].

The CO_2 emissions due to hydropower plant is estimated to be 85g CO_2e/kWh. By building hydropower plants with high land use per unit of electricity generated, the CO_2 emissions can be reduced [99].

2.7.4 Nuclear power plants

Nuclear power plants generate electricity by the fission of nuclear fuel- nuclear power plants are classified as thermal generators since the current technology makes use of the heat generated by a nuclear reaction [99 – 101].

Benefits with nuclear power generation is that it is a low carbon energy source where the process produces close to no greenhouse gas emissions, the radiation produced during nuclear fission can be efficiently screened, it is efficient, cost effective, failures are uncommon. Last but not least, there are huge uranium reserves, they should cover the humanity's energy needs for several hundred years [103, 104].

Failures, on the other hand, while uncommon, can be extremely harmful. So far, solely two accidents have happened – in Chernobyl (1968) and Fukushima (2011). These breakdowns were categorized as major accidents. However, the outcomes of such accidents are important, as they international influence. Radioactive waste the essential disadvantage when looking at nuclear power production. The storage of radioactive is one of the largest issues associated to nuclear energy. These issues are the main reason for the minimization in global nuclear electricity generation [72, 105, 106].

As of today, there are no nuclear power plants running in Norway. There are huge domestic thorium reserves that could be used as nuclear fuel. The usage of thorium allows for a safer and more environmentally friendly method of electricity generation than uranium, which is currently used in most reactors. In light of this, a public committee was formed to investigate the feasibility of incorporating this resource into future Norwegian electricity generation. The report, which was delivered in February 2008, advocated for further international cooperation in core technology as well as the development of its own competence in the field. Although the technology is not yet developed enough to be deployed, the committee suggested that the possibility of using thorium-based nuclear energy in the future must be kept open [107].

Several lifecycle analyses from all around the globe are done regarding nuclear power plants. Though these studies CO_2 emissions ranging from 1,4 g CO_2e/kWh to 288g CO_2e /kWh, with an average of 66g CO_2e /kWh [108].

2.7.5 Geothermal power plants

The Earths thermal energy is used to generate electricity in the geothermal power plants. The energy is extracted from deep down in the crust, where the temperatures are high. Fluid circulation through hot springs or heated rocks returns the heat to the surface [72].

Groundwater pollution and the release of hydrogen sulfide and other pollutants into the environment are two potential concerns when it comes to geothermal electricity generation. To use geothermal energy to generate power, the hot spring temperature must be greater than 150 degrees Celsius, and the depth must not exceed 3000m, and water needs to be consumable [72].

When looking at Norway, there are only a few areas where geothermal heating is used. As for 2018 energy extracted from the ground is estimated to be about 3 TWh per year [109]. When comparing to Iceland, which is surrounded by hot springs, and where 29% of all electricity production comes from geothermal energy, geothermal power plants is more suitable for areas with hot springs [72].

A running geothermal plant will have some emission of greenhouse gases like CO_2, which is the main environmental concern. The power plant itself has a low carbon footprint, and the emission from volcanic origin that is released during digging. The emissions are measure only 5-6% if geothermal power plants are compared to a fossil-fuel burning power plant [110, 111].

2.7.6 Combined energy production

Currently, Rosenberg Worley is working on a floater that is supposed to combine energy production from both solar, wind and hydropower. This project is called Flex2power, ad I based on a floating and flexible steel foundation. As the foundation moves due to the waves at sea, hydro power energy is collected and converted to electricity via hydraulic systems and generators. On top of these generators, solar panels are being mounted to collect as much solar power as possible. The wind turbines are installed inn each corner of the fundament [46]. The Flex2power project is visualized in Figure 21.

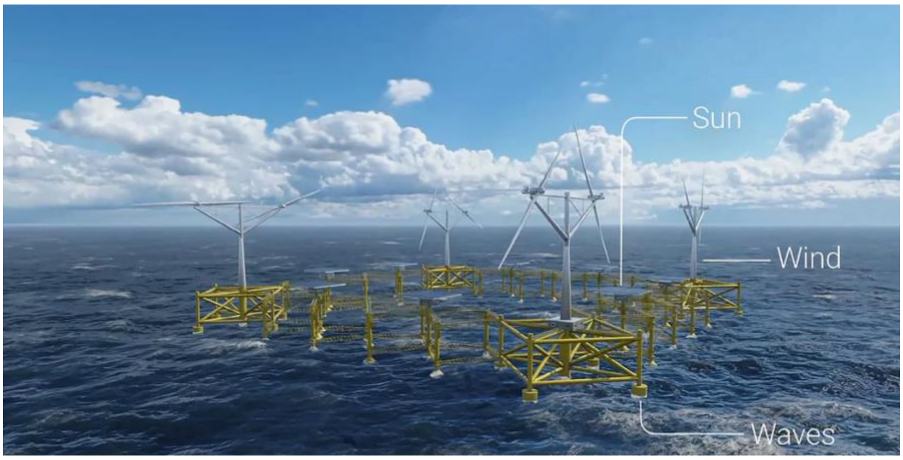

Figure 21: Rosenberg Worley's Flex2power offshore energy producing floater system [46].

The Flex2power solution combines energy production from several areas, thus being both cost and area effective [46]. A Flex2power park will only use 16% of the are compared to installations that would produce the same amount of energy [112].

The pilot product, consisting of only one wind turbine, one wave generator module and one solar panel foundation had the total installed capacity of 10,2 MWh. When looking at the whole life span of the system, it is assumed that the pilot will produce 1,34MWh in 25 years [112]. Figure 22 show the a detailed Flex2power pilot.

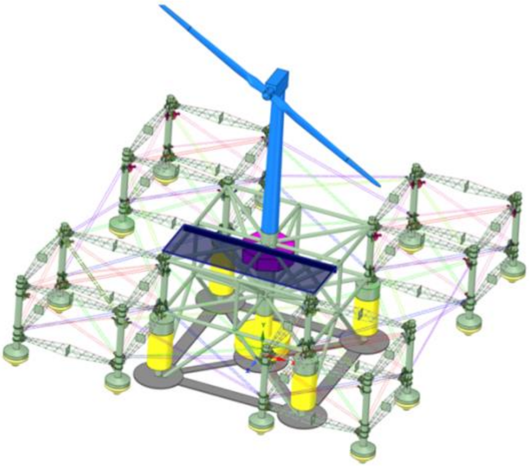

Figure 22: Roseberg Worley's Flex2power pilot project [112].

2.8 Risk Analysis

Many customers also include the value of HSSE factors such as reduction in ignition sources, vibration, and noise, and reduction in risk of maintenance operations such as heavy lifting operations. These are difficult to include in a basic cost calculation as they will vary considerably between operators. Even so, these factors are often cited as the most important to workers at the facility. Reduced maintenance intensity offers the opportunity for reduced facility staffing or remote operations/remote operations support. This was one of the main factors for the selection of Power from Shore in the BP Valhall redevelopment project [113].

If the power suddenly is lost or reduced, a safety net of stand by gas turbines starts to run. The gas turbine safety net reduce the risk of blackout at the electrified offshore installations [49, 51, 114].

There are also risks connected to the implementation of electrification. As most of electrified project focuses on already existing offshore installation there are some risks connected to the modification phase. During this phase it is expected that there are higher risks of major accidents and personal injury [20].

In the operational phase, there are risks due to the removal of ignition sources and the combustion gas system. Gas turbines are considered as one of the major ignition sources on oil and gas platforms. If gas is leaked, huge gas clouds can be formed, which is dangerous for human beings. When removing the gas turbines from the offshore installation, an ignition source is removed, and the risk of major accidents is reduced. When turbines are removed or pacified there is no need for combustion gas system. These systems are often less robust, when exposed to vibration, it may cause a gas cloud, and possibly an explosion or a fire [20].

As gas turbines is a high maintenance tool, operators are needed at the installation to make sure everything is going well with the gas turbines. When these are removed, and replaced by electric motors, which require less maintenance, personnel are released. As flying in helicopter is one of the riskiest activities in the petroleum industry, this will possibly lead to less personal injury [20].

Gas turbines produce noise and vibration at the offshore installation. When removed the noise and vibration are reduced and will have a positive impact on the work environment on the installation. Lastly, the gas turbines releases exhaust gases, that enters the ventilation system. This is bad for the environment on the installation. If gas turbines are removed, the risk of exhaust gases in the ventilation system is reduced [20].

As a modification project require lots of hours for hot works, the risk of fires due to hydrocarbon leaks, is increased during this period. Even if the risk of major accidents happens during the modification phase, statistic show that there is a lot of modification projects that have happened the last years, with non-leakage of hydrocarbons that potentially can cause a fire. In the modification phase a large amount of personnel is needed at the installation. This increases the risk of helicopter accidents. The modification phase will pass eventually, ant the risks for major accidents and personnel injury is removed [20, 115].

When removing turbines and installing new heavy equipment like modules, heavy lifting operations is happening. With the right preparation and experience, risks of accidents due to heavy lifting operations are negligible [20]. For heavy lifting operating the three major hazards that could happen is falling materials, overloading, and electrical hazards. About 50% of all accidents in crane operations is electrical hazards, because of the machinery coming in contact with a power source. If a crane lifts to much weight, exceeding its capacity, structural stress that causes damage on the crane may occur. This can lead to swinging and dropping the load [116].

In the cases with PFS to the fields where DC transmission is necessary, a separate facility is needed for converting DC to AC. This facility is also needed for the distribution to relevant facilities in the area. The conversion equipment that converts DC to AC has a significant volume and space requirements, and risks connected to heavy lifting operations may arise [20].

2.9 Cost of offshore electrification

When looking at offshore electrification, reduced maintenance costs play an important role of the economic picture. The electrification of offshore installations results in increased stability, availability, and energy efficiency. In the light of these points, electrification has the possibility to improve the operational economy of the installation. To achieve these assumptions, it is considered that the provided energy originates from renewable energy sources [113].

When changing from a thermodynamical system to an electrical mechanical system, the response time is significantly increased. This results in major improvement in the stability of the offshore installation by preventing process trips and increasing availability, increasing the effective full production days per year. A variable speed drive can still provide the torque required to start a fully loaded compressor even in case of a shutdown. As a result, most compressor applications benefit from this characteristic, as it both saves time and eliminates flaring of gas. Economic, operational, and environmental benefits follow from these factors [113].

When using natural gas for power generation, CO_2 is emitted in the process. When emitting this greenhouse gas, the CO_2 tax must be paid, which has increased from 340 NOK ($35) to 650 NOK ($67) per ton of CO_2. Therefore, reducing greenhouse gas emissions can result in lower operating costs and potentially higher energy savings, and this can be achieved by electrifying offshore installations by sourcing power from shore or by generating electricity on-site [9, 117, 118]. It is assumed that for Norway, the CO_2 tax will increase to 1960 NOK ($200) per ton of emitted CO_2 by 2030 [119].

A study done by Cheng et al. (2017) show the annual total system operation cost of different cases with and without electrification. The study take bot the CO_2 price elements and emissions costs due to CO_2 into account. The study shows the annual cost of eight different cases, ranging from no, part- and full-electrification. This study is summed up in Table 1 [120].

Table 1: Overview of the cases (1-8), the electrification degree, cost of CO_2 and total costs for each case [120]. The data is converted from euro to NOK with the rate 1 euro = 9,80 NOK.

Case	Degree of electrification	CO_2 cost in NOK/ton	Total cost in billion NOK per year
1	No electrification	0	286,3
2	No electrification	304	426,5

3	Full electrification	304	434,3
4	Full electrification	243	408,8
5	Full electrification	370	459,8
6	20% electrification	304	428,4
7	50% electrification	304	430,4
8	80% electrification	304	433,3

Comparing the cases (2, 3, 6, 7 and 8) with CO_2 costs of 304 NOK/ton, no electrification has the lowest total cost of 426,5 billion NOK/year. Case 4, which is full electrifications, has the highest costs with 434,3 billion NOK/year. The part electrification cases lies in between and varies from 428,4 to 433,4 billion NOK/year [120].

Cost estimates for the electrification of the North Sea only, show that there is a cost ranging from 1350 – 3100 NOK per ton of reduced CO_2. When looking at the Norwegian sea, the cost estimate ranges from 1550 – 2150 NOK pr ton of reduced CO_2. Table 2 sums up the total cost per year for part and full electrification of the North Sea and the Norwegian Sea [121].

Table 2: Total cost per year for different electrification scenarios in the North Sea and in the Norwegian Sea. Data collected from Lundberg and Kaski (2011) [121].

Area	**Degree of Electrification**	**CO_2 savings in tons/year**	**Cost for CO_2 saved in NOK/ton**	**Total cost per year in NOK**
The North Sea	Full	6 500 000	2225	14,5 billion
The North Sea	Part	2 120 000	2225	4,7 billion
The Norwegian Sea	Full	1 680 000	1850	3,1 billion
The Norwegian Sea	Part	700 000	1850	1,3 billion

As mentioned, lots of electrification projects require modification of already existing oil and gas platforms, which require lots of steel. The levelized costs of steel is 5865 NOK/tls – 6808 NOK/tls (\$622/tls - \$722/tls) [122]. Another cost analysis of steel show prices ranging from 3648 – 6467 NOK/ton (€361-640/ton) of steel. The prices of steel is highly dependent on the electricity and CO_2 tax prices [123].

Electrification of offshore platforms seems to optimize the production potential. This will result in a reduction development costs. Together with improved scheduled, electrification will lower the CAPEX (Capital Expenditures) costs of offshore platforms [124].

2.10 Potential of electrification

As only 50% of the recoverable petroleum reserves on the NCS is produced, it is expected that the oil and gas industry will last for many more years [125]. The electrification of offshore oil and gas platforms will most likely result in an extended lifetime for the petroleum industry, that will generate work to both onshore and offshore workers within the petroleum industry [126]. Electrification using PFS will provide a long, stable and environmental friendly power supply [127]. The efficiency will increase for electrified offshore oil and gas platforms and is one of the key drivers for the transition to a green hydrocarbon production. The increase of efficiency is said to be the most cost-effective way towards an environmental friendly production [128]. As of today there are both electrification in the Barents Sea, the Norwegian Sea and the North sea [127, 129, 130].

In addition to the electrification of offshore platforms on the NCS, there is potentials for electrification of subsea installations in the Arctic regions [131].

The southern parts of the North Sea, including Ekofisk, Eldfisk, and Ula has large potentials for electrification. The power balance in the area is sufficient and can handle to power offshore oil and gas platforms. Assumed reduction in CO_2 emissions due to full electrification in the area is 1,09 million tons/year. A part-electrification will reduce 420 000 tons of CO_2 annually [121].

The middle parts of the Nort sea, including Ringhorn, Grane, Johan Sverdrup and Sleipner also have the potentials to being electrified. Statnett indicate that the power grid can handle electrification of the middle part of the North Sea. Part-electrification of the area has the potential to reduce CO_2 emissions with 100 000 to 400 000 tons/year, while a full electrification of the area will assumingly reduce CO_2 emissions by 925 600 tons/year [121, 132].

The northern part of the North Sea, including Troll, Oseberg, Snorre, Gullfaks and Statfjord has large potentials for electrification. Estimates show that a part-electrification of the area has the possibility to reduce CO_2 emissions by 1,4 million tons/year. Estimates done for full electrification of the northern parts of the North Sea show that CO_2 emissions may be reduced by 3,7 million tons/year [121].

When looking at this as one unit, part electrification has the potential to reduce CO_2 emissions with 1,92 to 2,32 tons/year. Full electrification of then the North Sea has the potential to reduce ~6,5 tons CO_2 annually [121].

To extend the lifetime of the oil and gas platforms in the North Sea, electrification is a possibility. This will ensure production of oil and gas in the future, alongside with reduction of CO_2 emissions [121].

The Norwegian Sea includes the Åsgård, Njord, Draugen, Heidrun and Kristin fields. The major concer when it comes to the electrification of the Norwegian Sea is that the power grid in the Middle parts of Norway isn't stable enough. If electrification is done there is a potential to reduce CO_2 with 700 000 tons/year for part electrification, and 1,68 million tons/year for full electrification [121].

2.11 Ongoing Electrification Projects

In this section general information about ongoing and future offshore electrification projects will be given. A shallow look into electrification of Goliat, Johan Sverdrup Network (including Edvard Grieg, Gina Krog, Ivar Aasen Gudrun and Sleipner) and Troll A. Figure 23 provide a map of the NCS, showing the location of the Edvard Grieg (1) and the Goliat fields (2).

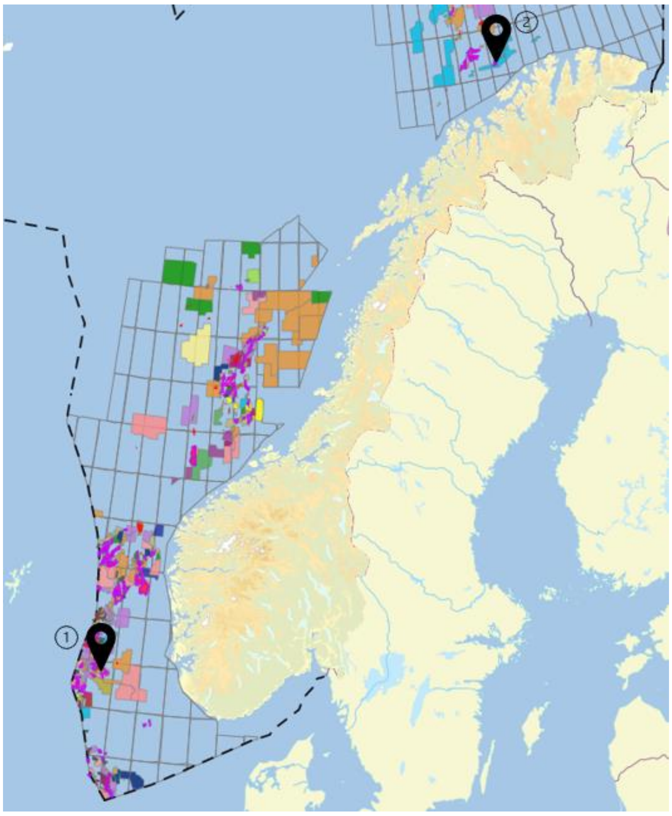

Figure 23: Overview of the Norwegian continental shelf, with Edvard Grieg field (1) in the North Sea and the Goliat field (2) in the Barents Sea [133].

2.11.1 Goliat

Goliat is an oil and gas field located in the Barents Sea, approximately 85 km northwest of Hammerfest. The Goliat field produces about 110,000 barrels of oil per day [130, 134].

Goliat is electrified by power from shore via electric cables on the seabed, as well as electricity generated on the platform. The main goal for the electrification of Goliat is to reduce CO_2 emissions from the platform by 50% [130, 134]. Goliat receives AC power transmission from a ~110 km long cable. The power supply is approximately 75 MWh [16].

2.11.2 Johan Sverdrup Network

The Johan Sverdrup field is located in the central parts of the North Sea, at the Utsira high, about 200 km from shore [16, 132]. With a production of 535 000 barrels of oil each day, Johan Sverdrup is the third largest oil field on the NCS. The field has only 4% CO_2 emissions as of today [135]. An overview of the Johan Sverdrup Network is shown in Figure 24.

Edvard Grieg is an oil and gas field located in the central parts of the North Sea, about 35km south from the Grand and Balder Field. The field produces about 5 million Sm2 of oil per day, which is equivalent to about 86162 barrels per day [136].

The electrification plans of Edvard Grieg started in 2019 and developed with the Johan Sverdrup Phase 2 project. The Edvard Grieg platform will be electrified via cables on the seabed from Johan Sverdrup with power from shore. The project will be operational by the end of 2022 and will significantly reduce CO_2 emissions from the field [137].

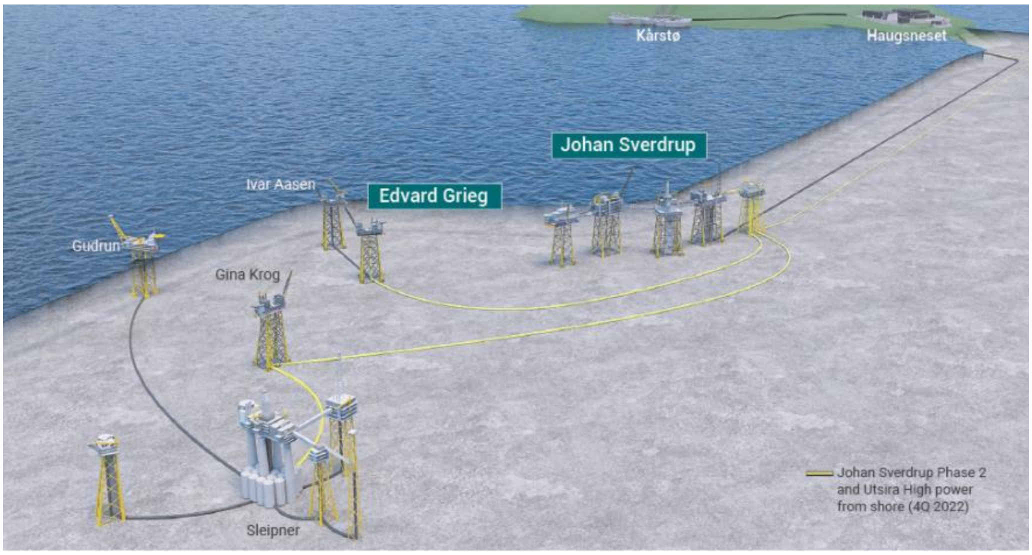

Figure 24: Overview of the Utsira High power from shore project [138].

2.11.3 Other Electrification Projects

Back in 1996, the electrification of the first offshore installation, Troll A, happened in on the NCS. The cable length from the shore to Troll A is about 70 km, which is considered a short distance. The Troll A platform have received power prom shore from both AC and DC transmission since 1996 [16].

Draugen is in the Norwegian Sea and has produced petroleum since 1993. The power demand is 40 MWh, and the transportation distance is approximately 130 km. The Draugen platform is one of few where the whole power demand is met by PFS [16, 127].

The Oseberg Field Center and Oseberg South is in the northern parts of the North Sea. The project is going to be electrified from the same land-based plant as the Troll West Electrification project. The cable is 120 km long, and will supply about 100 MWh with PFS [16, 73].

3 Case study description

The purpose of this section is to characterize the power demand of the case study of a full-electrificated and a part-electrificated platform on the Norwegian Continental Shelf. The criteria and limitations of the case study is described.

3.1 Site characterization

To analyze the feasibility and potential of offshore electrification for powering offshore oil and gas platforms, two currently operating platforms on the Norwegian Continental Shelf is considered as the case study due to the new electrification project happening on these platforms.

The selected platforms are located in the Troll West oil field, in the northern parts of the North Sea, approximately 65 kilometers west of Kollsnes, near Bergen. Troll West consists of the Troll B and Troll C platform. The platforms and the cable system are presented in Figure 25. The Troll field produces oil and gas and is the core stone of Norway’s oil and gas production, therefore a very important field for Norway [139].

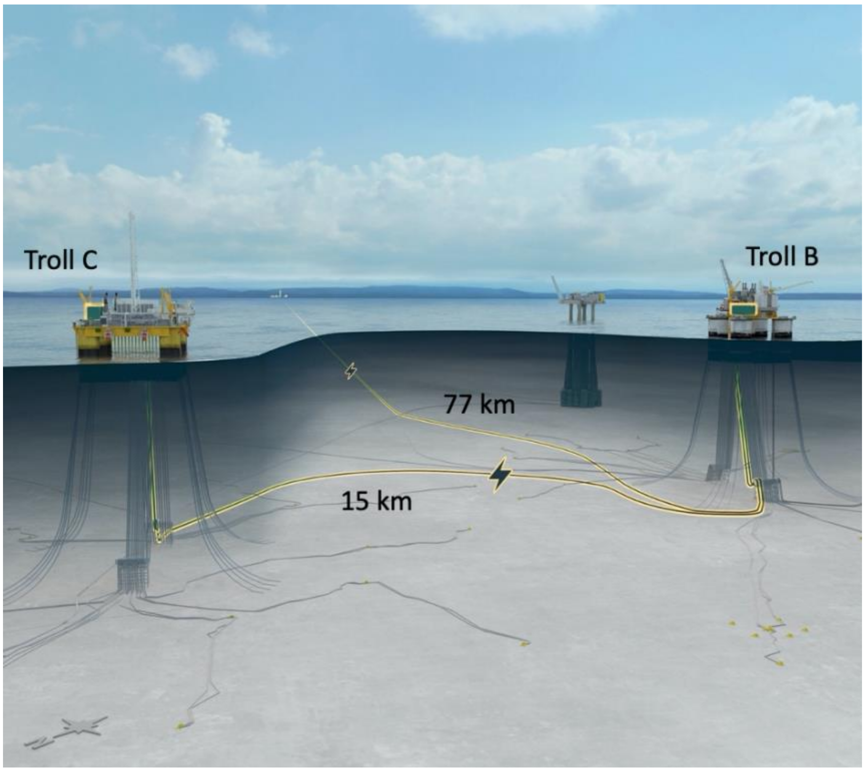

Figure 25: High-voltage subsea cables in the Troll West province in the North Sea [49, 126].

The total power demand of both platforms, which include part electrification of Troll B and full electrification of Troll C is 116MWh, including a transmission loss of about 9% [16], [49]. This power is going to be transported from a high-voltage subsea cable from Kollsnes to Troll B, and then from Troll B to Troll C. Both platforms are driven by the well-known gas turbines as of today [126].

The electrification of the Troll B and Troll C platforms is assumed du reduce large amount of CO_2 emissions. This is achieved by replacing the gas turbines with electricity from shore. The full electrification of the Troll C platform, and the part electrification of the Troll B platform, has the potential to reduce large parts of the annual CO_2 emissions at the Troll field [129, 140 – 144].

As of 2020 Norway emits 41,28 million tons per year. From 2000 to 2020 the annual CO_2 emissions show a decreasing trend. The Troll West Electrification project will show the possibilities for electrification, with respect of reduction of CO_2 emissions [126, 144, 145].

The power demand is provided by gas turbines, but to reduce the carbon footprint, it is decided to part-electrificate the Troll B platform and full-electrificate the Troll C platform. Troll B is partly electrified as a safety net in case of power failure. In case of failure, two GTs will provide power for two generators on Troll B, and one GT will provide power for one generator at Troll C [51].

There are two compressors driven by GT's running, and two GT driven generators standby on Troll B. The running GTs for the compressors provide 24MWh each. When Troll B is part electrified the generators are driven by electrical motors, and the compressors are driven by GT's. The standby GT generators are used island mode, to provide electricity to Troll B.

As for the full electrification of Troll C, the two gas turbines that drive two compressors and one gas turbine that drives one generator are changed into electric motors, For Troll C there is one standby gas turbine, that will cause one generator to provide enough power to run Troll C at reduced capacity, during island mode [49].

For the part electrification gas turbines are still running the compressors, while the power provided from the generators are replaced by PFS. For the full electrification of Troll C all power demand is provided with PFS [49 – 51].

The main reason for the part electrification of Troll B, is a safety net. If a blackout is happening, the two platforms will have an island mode [49, 50]. In this mode the four GTs on Troll B will run to drive two compressors and two generator, while one GT will drive one generator on Troll C. Troll B runs as normal, while Troll C runs at a reduced capacity during island mode [49, 51].

For the electrification on Troll West High-Voltage alternating current (HVAC) is used [146]. The reason for the use of HVAC instead of HVDC is mainly because the distance is short enough to use HVAC, that does not transport as far as HVDC. HVAC has a shorter transport distance because of the transmission loss. As AC power is used on shore, one needs a transformer on shore, then DC power goes through the cable, and must be transformed back into AC power because that is what is used on the platforms. These transformers are rather expensive. The choice of HVAC use is based on a cost-benefit assessment [49, 50].

The cable can transport power up to 170 MWh, which facilitates the possibility of a full electrification on the Troll B facility in the future [16, 49]. There is no plan to fully electrify the platform as of today [49, 50].

3.2 Case study limitations

- Lack of information about the two platforms involved, as the project is described as a whole project.
- In the case of no electrification, there is two GT driven generators and two GT driven compressors running on Troll B and Troll C [128].
- The compressors and generators run 365 days/year.
- The daily fluctuations of power, gas and oil price are ignored.
- 6.1 million Sm3 o.e. of oil left (Troll A, B, C) [147].
- 684.9 million Sm3 o.e. of gas left (Troll A, B, C) [147].
- Troll A is electrified, but not included in the Troll West Electrification project [16, 126].
- It is only the GT driven compressors and GT driven generators that emits CO_2 on the platform.

- For this case study, only the emissions from the GTs and production of steel for the modules is considered.
- CO_2 emissions because of the modification (fabrication of smaller structures, piping systems etc.) of the platforms, is not considered in these calculations.
- For this case study, the costs included are power costs, CO_2 tax costs, costs of modules and the cost of the HVAC cables.
- Operation and maintenance costs are not included in the model
- The costs for the onshore facility at Kollsnes are not considered.
- Process heat is not included in this case study

Other assumptions used in the case study are listed in Table 3 and Table 4.

Table 3: Cost assumptions used in the case study.

Item	Cost	Unit	Reference/ remark
Power Price	42,95	NOK/MWh	[71]
HVAC cable	10,87	MNOK/km	[49]/ Total for the whole cable 77+15=92 km is 1 billion NOK.
Oil	168,36	NOK/Sm3	[148]
Gas	3,36	NOK/Sm3	[130]
CO_2 tax	941	NOK/ton	[150]
Steel	5228	NOK/ton	[122], [123]

Table 4: Assumptions used in the case study.

Item	Quantity	Unit	Reference/ remark
Transmission loss	9	%	[49]/ included in power demand
Troll B power demand, PFS	33	MWh	[16], [126]
Troll B total power demand	81	MWh	[49]6/14/2022 3:07:00 PM

Troll C power demand, PFS	83	MWh	[16, 126]
CO_2 emission, one compressor	355,5	Tons/day	[51]/ Data is collected 25.04.22-25.05.22
CO_2 emission, one generator	342	Tons/day	[51]/ Data is collected 25.04.22-25.05.22
CO_2 emission, steel production	1,85	ton/ton	[24]

4 Case study

In this section a case study of full electrification at Troll C, and part electrification at Troll B will be carried out. The case study will give an insight of the CO_2 emissions, costs, and feasibility of electrification on the NCS.

4.1 General facility data and assumptions

The base case for Troll B and Troll C is equal, as both platforms have two GT driven compressors and two GT driven generators running [51].

The general facility data and the costs of the base case of each facility is provided in Table 5 and 6, respectively.

Table 5: General facility data of the base case with no electrification.

Item	Quantity	Emissions	Unit	Annual total emissions	Unit
GT Compressor	2	355,5	Tons/year	259 515	Tons/year
GT Generator	2	342	Tons/year	249 660	Tons/year
Total	-	-	-	509 175	Tons/year for each facility

Table 6: Costs for the base case, no electrification.

Configuration	Quantity	Unit	Cost	Unit	Annual total costs	Unit	Remark
Power from shore	0	MWh	42,95	NOK/MWh	0	NOK/year	No PFS for the base case
CO_2 tax	509 175	Tons/year	941	NOK/ton	479 133 675	NOK/year	Emiessions for 2 compressors and 2 generators running
Total	-	-	-	-	479 133 675	NOK/year	

On the Troll B platform there is not going to be removed any GT's. A new electrification module with a weight of approximately 950 tons is going to be installed. The Troll B platform is to be electrified by approximately 41%. There will be two gas turbines running providing 24 MWh each, and two generators powered with PFS. The total power demand for Troll B is 81 MWh, where 33 MWh is provided by PFS [49].

The assumptions made for the par electrification of Troll B are listed in Table 7.

Table 7: Assumptions for the part electrification case study.

Unit	Volume	Unit	Reference/ remark
Electrification module	950	ton	[51]
GT Compressor	2	NA	NA
GT Generator	0	NA	NA
Electrification degree	41	%	[49]
Cable lenght	77*0,2884	Km	[51]/ the cable length is multiplied with 0,2884 is 28,84% of the total power is provided for the part electrification of the Troll B platform.

The general facility data for the part electrified Troll B platform is presented in table 8.

Table 8: General facility data of the Troll B platform.

Configuration	Volume	Unit	Income	Unit	Total income	Unit
Oil Production	6375	Sm3/day	168,36	NOK/Sm3	1 073 295	NOK/day
Gas Production	6,892	MSm3/day	3,36	NOK/Sm3	23 157 120	NOK/day
Distance to shore	77km	km	-	-	-	-

The Troll C platform is to be electrified from shore via the Troll B platform. Troll C currently has two gas turbine that is going to be replaced with electric motors, to drive two compressors [49, 126]. A GT driven generator is also to be removed, leaving one GT driven generator. In addition to this there is to be installed a new trafo, a GIS (Gas Insulated Switchgear) and an electrification module. A NO_X facility is removed to make room for the GIS and trafo modules [51].

The assumptions made for the full electrification of the Troll C platform is represented in table 9.

Table 9: Assumptions for the full electrification case study.

Unit	Volume	Unit	Reference/ remark
GIS module	106	Ton	[51]
Trafo module	128		[51]
Electrification Module	650	Ton	[51]
GT Compressor	1	NA	[51]
GT Generator	0	NA	NA
Electrification degree	100	%	[51]
Cable lenght	77*0,7116 + 15	Km	[51]/ the cable length is multiplied with 0,7116 as the cable will provide electricity to both facilities, but 71,16% of the power required for the Troll C full electrification.

The general facility data for the Troll C platform is provided in table 10.

Table 10: General facility data of the Troll C platform.

Configuration	Volume	Unit	Income	Unit	Total income	Unit
Oil Production	8700	Sm3/day	168,36	NOK/Sm3	1 464 732	NOK/day
Gas Production	15,3	MSm3/day	3,36	NOK/Sm3	51 408 000	NOK/day
Distance to shore	77 + 15	km	-	-	-	-

4.2 CO_2 emissions

The calculated CO_2 emissions for the two running compressors, and for the steel required for the electrification module for Troll B is provided in table 11.

Table 11: Calculated CO_2 emissions for part electrification of the Troll B platform.

Item	Quantity	Emissions	Unit	Annual total emissions	Unit
Gas Compressor	2	355,5	Tons/day	259 515	Tons/year
Generator	0	342	Tons/year	0	Tons/year
Total	-	-	-	259 515	Tons/year
Steel production emissions	950	1,85	Ton/ton	1757,5	Tons

With no electrification, the total CO_2 emissions of each facility is 509 175 tons/year, combined this results in a yearly emission of 1 018 350 tons. Each platform has the same CO_2 emissions as there are two gas turbine driven compressors and two gas turbine driven generators that emits CO_2 on them both.

As the total emissions of CO_2 on the Troll B facility without electrification is calculated to be 509 175 tons/year and the emission on the platform when part electrified is calculated to be 259 515 tons/year, a total of 249 660 tons of CO_2 is reduced per year, when changing two GTs that drive the generators with electric motors driven by PFS. When 41% electrified, two gas turbine compressors will emit CO_2. This equals to a CO_2 reduction of 51% annually. In the case of island mode, Troll B will emit 1395 tons of CO_2 each day.

The calculated CO_2 emissions of the different items included for Troll C is provided in table 12. The emissions considered is emissions to produce steel required to build the electrification, GIS and trafo modules.

Table 12: Calculated CO_2 emissions for full electrification.

Item	Quantity	Emissions	Unit	Total emissions	Unit
Gas Compressor	0	355,5	Tons/day	0	Tons/year
Generator	0	342	Tons/day	0	Tons/year
Total	-	-	-	0	Tons/year
Steel production emissions	234	1,85	Ton/ton	1635,4	Tons

With no electrification, the CO_2 emissions on the Troll C platform is calculated to be 509 175 tons/year. When fully electrified, there is no emissions as the gas turbines that are used to drive the two compressors is replaced by electric motors, which are run by PFS. One gas turbine is remained as backup in case of blackout. There is saved 509 175 tons CO_2 per year when replacing the GTs with electric motors to drive the compressors. This corresponds to a 100% CO_2 reduction. In the case of island mode, one running GT driven generator will emit 342 tons of CO_2 each day.

The total CO_2 savings of both facilities is 758 838 tons/year, resulting in a yearly reduction of 74,52% for the whole Troll West Electrification project.

The calculations of CO_2 emissions in this case study will not match the detailed engineering analysis done by Equinor, due to several limitations and lack of technical inputs. The estimates provided in this case study show the potential of electrification for CO_2 reduction, which is huge.

The annual CO_2 reductions and emissions of Troll B and Troll C is shown in Figure 26. The Figure shows that full electrification has a significantly lower CO_2 emissions on a yearly basis, when compared to part electrification, as there are no emissions for the full electrification case. For these CO_2 emissions, the one-time emissions due to production of steel is not included. These emissions make up 1757,5 tons for Troll B and 1635,4 tons for Troll C, before the project is up and running.

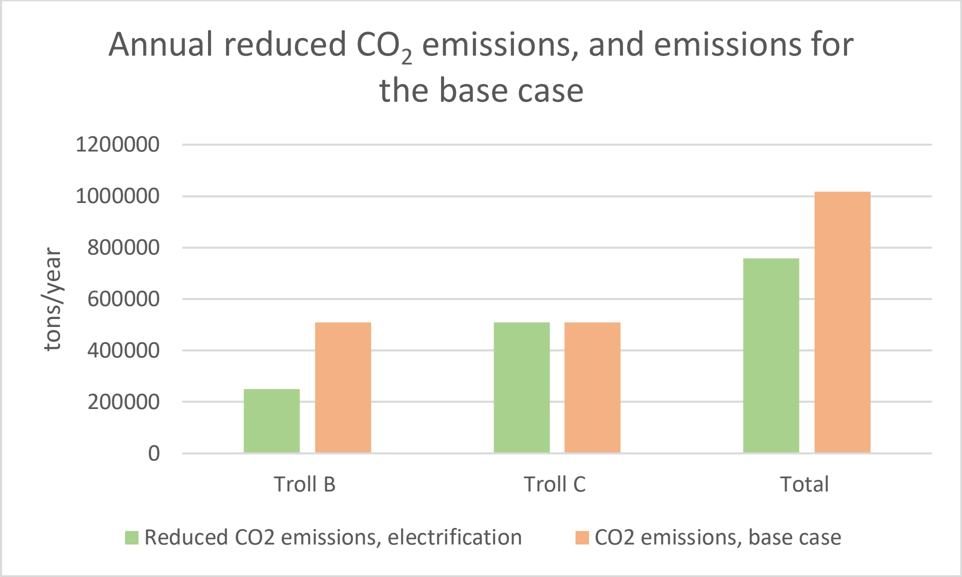

Figure 26: Annual CO_2 reduction and emissions for the base case, for the partly an fully electrification cases.

Offshore electrification has the potential to reduce large future CO_2 emissions, up to about a ~75% reduction. This reduction is needed to keep the offshore industry up and running for many years. When comparing no electrified platforms with the electrified ones, offshore electrification is proved to reduce CO_2 emissions when replacing power generated from gas turbines and gas turbine driven compressors with PFS. Both part- and full electrification may be good options when looking at the electrification of the NCS. Even if part electrification has lower potential in CO_2 reduction when compared to full electrification, there is no doubt that part electrification is a possibility.

If the there is a blackout and the platform goes into island mode, two generators and two compressors will run at Troll B, and one generator will run at Troll C. This will result in a CO_2 emissions of 1737 tons of emitted CO_2 per day. This will of course happen from time to time, planned due to maintenance and maybe even unplanned. This will have impacts on the CO_2 emissions picture.

4.3 Costs for electrification

The calculated costs for the part electrification of Troll B and the full electrification of Troll Care represented in table 13 and 14, respectively. The total costs of each configuration are given in either NOK/year or NOK.

Table 13: Calculated costs for part electrification of Troll B.

Configuration	Quantity	Unit	Cost	Unit	Annual total costs	Unit
Power, 9% transmission loss	33	MWh	42,95	NOK/MWh	12 415 986	NOK/year
CO_2 tax, emissions	259 515	Ton/year	941	NOK/ton	244 203 615	NOK/year
CO_2 tax, steel production	1757,5	Tons	941	NOK/ton	1 653 807,5	NOK
Electro module	950	Tons	5228	NOK/ton	4 966 600	NOK
Cable	77*0,2884	Km	10 869 565	NOK/km	241 278 265	NOK

Table 14: Calculated costs for full electrification of the Troll C platform.

Configuration	Quantity	Unit	Cost	Unit	Annual total costs	Unit
Power, 9% transmission loss	63,8	MWh	42,95	NOK/MWh	31 570 311,6	NOK/year
CO_2 tax, steel production	1635,4	Tons	941	NOK/ton	1 538 911,4	NOK
GIS module	106	Tons	5228	NOK/ton	554 168	NOK
Trafo module	128	Tons	5228	NOK/ton	669 184	NOK
Electrification module	650	Tons	5228	NOK/ton	3 398 200	NOK
Cable	77*0,7116	Km	10 869 565	NOK/km	595 578 249	NOK
Cable	15	Km	10 869 565	NOK/km	163 043 475	NOK
Total cable	66,3282	Km	10 869 565	NOK/km	758 621 724	NOK

The CO_2 tax cost analysis on the emissions happening on the platform on a yearly basis show that no electrification has the highest costs with approximately 479 million NOK annually. With part electrification of Troll B the CO_2 tax is approximately 244 million NOK annually, this is a reduction of ~51%. For the full electrification there are no costs due to emissions of CO_2 on the platform, which reduces the costs with 479 million NOK per year, which corresponds to a 100% reduction in CO_2 tax costs.

The CO_2 tax is a hot topic when looking at the economic picture of offshore electrification. As the CO_2 tax is assumed to increase in the coming years, this picture will of course change. With the tax increase, the costs of no electrification will increase, making electrification even more economic than today.

There are also one-time CO_2 tax costs due to the production of steel required for the two electrification, GIS and trafo modules. The total CO_2 emission tax for the electrification module at Troll B is approximately 1,65 million NOK. For Troll C the three modules will result in a one-time CO_2 emission tax of about 1,54 million NOK. In the big picture, these costs are considered rather small.

The module costs and the cable costs are one-time costs. The electrification module on Troll B cost is 4 996 600 NOK, which is considered a one-time cost. Another one-time cost is the cost of the power cables. The power cable to Troll B costs 241,28 million NOK. The total one-time costs (module and power cable costs) for Troll B are 246,24 million NOK.

The one-time costs for the full electrification of Troll C are higher when compared to Troll B. This is because there are more modules needed for the full electrification, and there is more cable needed. The 77km cable from Kollsnes to Troll B will provide power to both platforms. As the PFS power demand of Troll C is 83 MWh and the PFS power demand for Troll B is 33MWh. 71,16% of the power in the 116 MWh cable from Kollsnes is needed for Troll C, while the remaining 28,84% is needed for Troll C. Resulting in Troll C taking the costs for 71,16% of the 77km HVAC cable from Kollsnes to Troll B, and the 100% of the HVAC cable from Troll B to Troll C. The GIS and trafo module costs are 554 168 NOK and 669 184 NOK respectively, while the electrification module for Troll C is 3 398 200 million NOK. The power cable system for Troll C costs 758,62 million NOK. For the Troll C platform, the total one-time costs (module and power cable costs) are 763,24 million NOK.

The annual power cost of the entire project is 44,12 million NOK per year. This includes a power cost of 31,57 million NOK annually for Troll C, and 12,41 million NOK annually for part electrification of Troll C. The Troll C is accountable for 71,16% of the power costs in the project. A transmission loss of 9% is assumed to be included in these calculations. These numbers are represented in Figure 27.

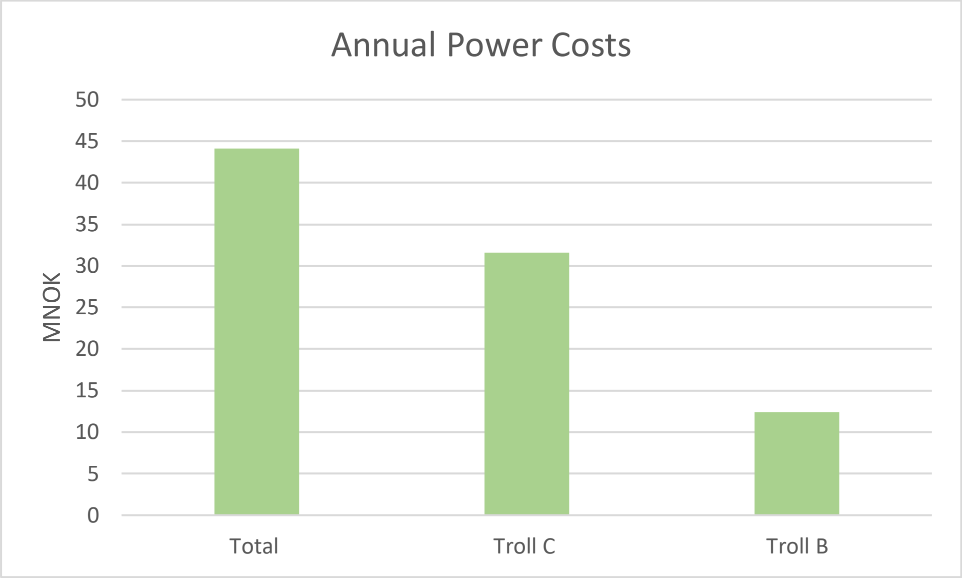

Figure 27: yearly power cost of Troll B and Troll C

Combining all the costs, the total costs for the first year for the Troll B and Troll C platform is 492,20 million NOK and 796,35 million NOK, respectively. When the one-time costs aren't included the yearly costs for the Troll B platform is 256,62 million NOK. For the Troll C platform, the annual costs are 31,57 million NOK when one-time costs aren't included. Figure 28 represent these costs, and visualizes that full electrification has the largest startup costs, but considerably lower costs in the following years, when compared to the part electrified case.

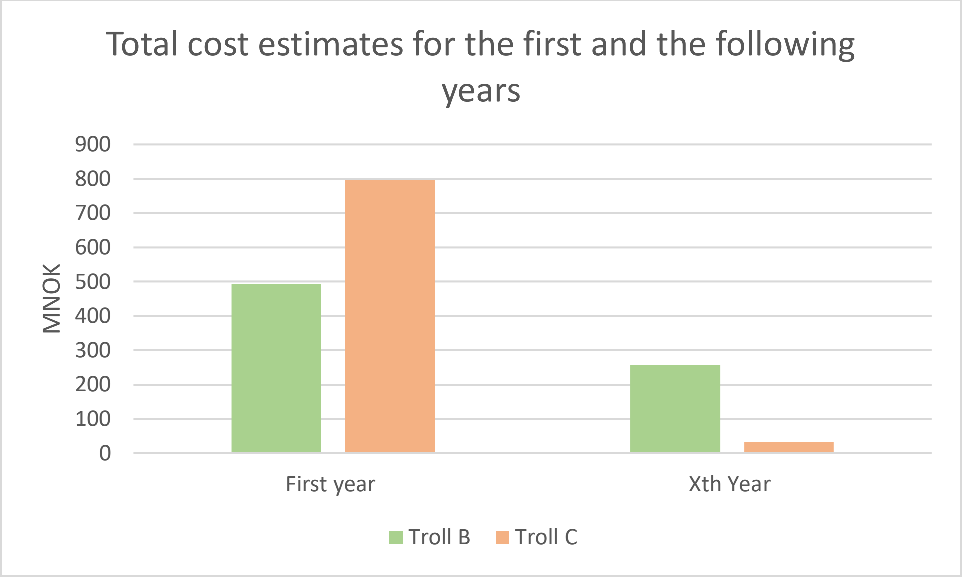

Figure 28: Total costs for the first and future years for the Troll B and Troll C platform.

The total cost of the project is the module costs, power cable cost, CO_2 tax cost and power cost for the first year, as the module and power cable costs are one-time costs. As there are some costs connected to the modules and cables, which is considered one-time costs for the first year only, the cost of electrification is higher compared to the coming years. When looking at the next years, only CO_2 tax and power costs is used. As the CO_2 emissions, CO_2 tax, power demand and power costs is considered constant, the costs in the future will be constant on a yearly basis. When evaluating the total costs of the project on a yearly basis, it is shown that the total costs of Troll B will be lower than for Troll C during the four first years. After four years, the one-time costs of the modules and cable system for Troll C is neutralized by the lower CO_2 tax costs for the platform.

The cost calculations in this case study will not match the Equinors cost assumptions, due to several limitations and lack of technical inputs. The estimates for costs will for sure give insight inn the costs because of offshore electrification, even if they don't match Equinors numbers.

To get a somewhat clear picture, costs of the modules, cable, CO_2 taxes and power costs is combined for the first year. As a simulation for the future, the annual costs of CO_2 tax and power costs is added year by year. This to illustrate the whole economic picture. As Figure 29 shows, the startup costs for full electrification are higher than for part electrification. Due to the low CO_2 tax cost for full electrification projects, this seems to even out after some time. For this exact case, the full electrification is more economic than the part electrification after only ~2,5 years.

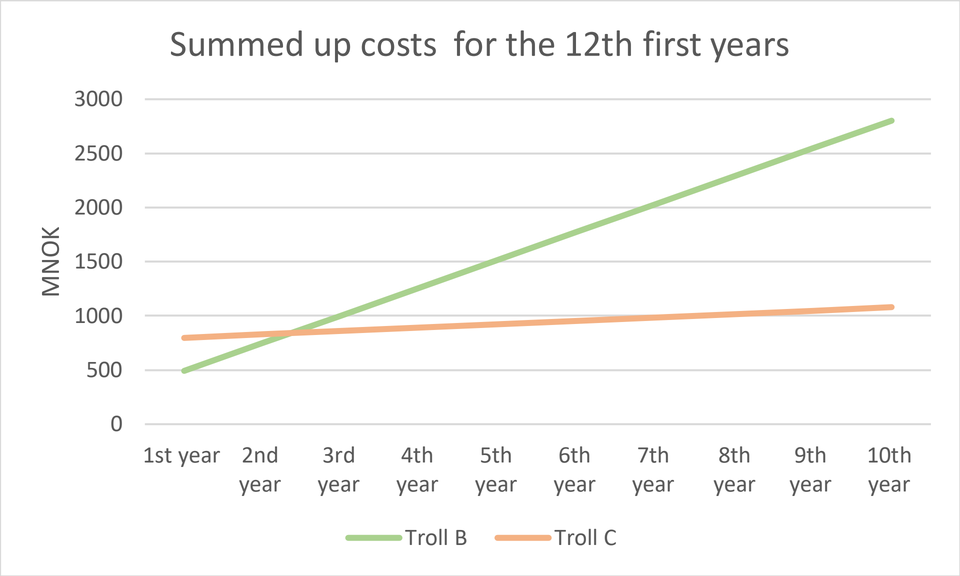

Figure 29: Total costs in the future for Troll B and Troll C.

There are with no doubt, large costs because of the transition to offshore electrification. As most electrification projects is implemented on already existing platforms, huge modifications are most likely to be needed. A lot of elements on the platform need to be removed to fit in the new electrification- GIS- and/or trafo modules. For such huge modifications, there are a lot of smaller structures and piping system that also is needed. For example, new access platforms, or maybe a new piping routing for the ventilation system or fire water. The needed amount of steel will of course vary from platform to platform. With no doubt the steel requirements make up a great deal of the costs of electrification.

The power supply will also make up costs for the electrification projects. We must pay for the daily power provided, not yet alone the cables from the power source. If power from shore is preferred, the cable costs are considerably higher than for cables needed if power is provided near the platform via i.e., offshore wind farms like Hywind Tampen. If one is to use power generated by i.e., offshore wind farms or floating solar cell panels, the cost due to the design and fabrication of these must be considered and included.

Another cost connected to the electrification of the NCS is the CO_2 emission tax. Even if both the full- and part electrification of offshore platforms result in less CO_2 emissions, the CO_2 emission tax is still a part, as the platforms most likely will emit some amount of CO_2. Also, there are CO_2 emissions due to the production of steel, that needs to be considered for modification. In the long run, the reduced CO_2 emission taxes will make up for the CO_2 emission taxes because of steel production.

If the platforms go into the island safe mode, it will as mentioned be released 1737 tons of CO_2 per day. This will result of a daily CO_2 tax cost rate of 1 634 517 NOK.

4.4 Potential

Electrification will result in an extended petroleum production and lifetime of the platforms. As there are a yearly income of 8,84 billion NOK for Troll B and 19,3 billions of NOK for Troll C, total income from petroleum production is 28,14 billion. Together with the total costs for electrification, there is a total earning of 27,12 billion NOK for the first year, and 28,12 billion NOK as a yearly income from the Troll B and Troll C platform combined, when every parameter used in the calculations is kept constant.

These estimated potential income from the Troll field is based on the recoverable amount of oil and gas, without considering operations and maintenance costs of the platforms. The actual income will be affected by these costs and might change with variations in market prices and the other associated costs described.

When speaking about offshore electrification, one question that may be arisen is: What is happening to the power prices today? With no doubt, the electrification of the continental shelf will need enormous amounts of power provided from the Norwegian power grid if power from shore is chosen.

The main point for electrification on the continental shelf is to get as high electrification degree as possible, to reduce as much emitted CO_2 as possible. At the same time the access and availability of power must be considered.

Do we have enough clean energy to operate with the power consumption if offshore electrification is widely implemented, is another question that pops up when we think about offshore electrification. As Statnett stated there is not enough power in the Norwegian power grid if it's supposed to supply all household and all industries in Norway in addition to meet the power demand from the possible electrified offshore installation. If the power consumption is supposed to increase, then the power production needs to be increased. Increased clean power production will possibly ruin the rivers and be converted to regulated water reservoirs.

As Statnett stated, there is not enough power to electrify the Norwegian continental shelf without supplying more energy to the power grid. Electrifying offshore oil and gas platforms will possibly drain the country from most of its power. The oil companies that wager on electrification of the continental shelf needs to stand in line like everyone else supplied by the Norwegian power grid.

To get enough power to supply all with electricity, more energy from renewable sources is needed. If an increase in the clean power production is achieved, another question rises. The transmission network is already overloaded. Will the solution be to build new power lines? And if so, the question about preserving nature rises once again.

The most efficient form of clean energy is with no doubt hydropower or nuclear power plants. If we expand what we already have, and utilize what we already have, parts of these questions are answered. An upgrade and expansion of the transmission network in Norway is needed if one is to electrify the whole NCS, this will possibly result in huge costs for Norway as a country.

As for Norway as a country, hydro- and wind power seems like the best options regarding clean energy production. Both sources have the potential to produce a significant amount of clean energy, with low CO_2 emissions. As hydro power already produces 91.8% of the electricity, maybe we need to look at the other alternatives. When comparing onshore and offshore windmills, offshore windmills are the preferable choice for Norway. This is because the wind conditions at the Norwegian continental shelf is better compared to the conditions onshore.

There are some risks connected to the electrification of the NCS. What do we do if a blackout is happening? For the Troll West Electrification project, Troll B is part electrified as a safety net. If a blackout is happening, the two generators and two gas turbine driven compressors on the platform will be able to fully run both Troll B, and keep the production as usual, which is called island mode. The standby GT at Troll C will be able to run one generator, that will keep the platform running and producing at reduced capacity.

For electrification networks like Troll West Electrification and Johan Sverdrup Network, part electrified platforms this could be a solution to prevent the total blackout of electrified offshore platforms. Which will minimize the economic losses happening due to a blackout. Even it will be emitted some CO_2 during the island mode, the overall CO_2 reductions of electrification projects will equalize these.

Other risks for electrification are highly connected to the modification phase. There are risks such as heavy lifting operations and gas leakages. With the right HSSE mind and experience, these risks are not likely to happen.

On the other hand, the electrification of offshore installation will reduce some risks connected to working offshore. The HSSE risks due to noise and vibrations from running gas turbines, is removed, or minimized as the gas turbines are either completely removed or and reduced number of gas turbines are left. As the electric motors require less maintenance than gas turbines, the required number of offshore workers may be reduced. This will reduce the risk of personnel injury because of helicopter accidents. Also, a lot of possible ignition sources are removed, which reduces the risk of explosions, gas clouds and fires.

Altogether, there are negligible risks connected to the electrification of offshore gas and oil platforms when the modification phase is finished.

Electrification of offshore installations may not be that relevant if the country is dependent on fossil fuels. As of today, many countries are dependent on this, and that maybe a reason why electrification isn’t a global topic these days. For these countries, development towards clean energy production via hydro-, wind-, solar-, geothermal-, and nuclear power is the first step in the direction of reducing CO_2 emissions. Due to the catastrophic history regarding nuclear power plant, this is probably the least popular option for clean energy production.

Due to the reduction of CO_2 agreed upon in the Paris Agreement, electrification may be the way to go. Not only will we continue to earn money for Norway as a welfare state, but it will result in keeping 200 000 of the workers that are linked to the petroleum production on the NCS working. If the oil and gas cranes in Norway shut down, due to us not being able the reach the emission goals within the Paris Agreement, huge consequences will happen. A lot of people will lose their jobs. As the petroleum industry are accountable for hotel stays and conferences in all parts of Norway, these also will lose a part of their income. And at last, it all will just spiralize into one big loop of consequences harming different workplaces in Norway like hotels, air fare, restaurants, taxis, shops and so on.

5 Conclusion

The thesis focused on the whole chain of offshore electrification, with the main focus on the feasibility of offshore electrification on a general basis. As a result of electrifying the NCS, more power is needed on the Norwegian power grid. To provide more power, hydropower, solar power, and wind power are the best alternatives to clean renewable energy sources. Using both quantitative and qualitative methods the thesis discusses the feasibility of offshore electrification. Based on literary papers and case study, the thesis summarizes some of the crucial aspects:

- The literature review and the case study conclude that electrification has the potential to reduce a huge amount of CO_2 from the petroleum industry. Even if the costs are high, it will result in lower CAPEX and a financial gain for Norway in the long run.
- Part electrification will also reduce CO_2 emissions from the petroleum industry, but they are considerably lower compared to the full electrification initiatives. The estimates done in the cost analysis of the full electrified and the part electrified platform show that the full electrified platform will be more economic than the part electrified platform after just a couple of years. It should also be mentioned that a part electrification is a safety net that could minimize accidents and economic losses happening because of blackouts.
- Power from shore to electrify offshore oil and gas installation might not be a solution for counties where they are dependent on fossil fuels for power production. As 91,8% of the electricity originates from hydro power in Norway, electrification is a solution for CO_2 reduction for the petroleum industry.
- As only 50% of the available petroleum resources have been produced and sold, there are equally as much left. This indicates petroleum production for many years to come. The electrification of offshore oil and gas platforms will secure a clean petroleum production in these years.
- The case study shows that the electrification of the NCS is highly possible and necessary for Norway as a country, with respect to reducing CO_2 emissions, extend the lifetime of the petroleum industry and Norwegian economy.

- As the major costs in the petroleum industry is the is the CO_2 taxes, it is obvious that the reduced CO_2 emissions as a result of offshore electrification will make the electrification of the NCS be even more economic if the CO_2 taxes increases as predicted in the near future.
- The Troll West Electrification project has the potential to reduce the total CO_2 emissions in the Norwegian petroleum industry by 5,85%.

When looking at the risks and costs as a result of electrification, it is clear that the potential to electrify the NCS is there, both with respect to reduce CO_2 emissions in the petroleum industry, and when looking at it economically. The technologies of full and part electrification are still not mature enough, and with no doubt more research is needed.

The case study can be evolved in the future to assess the electrification of offshore platforms under various oil and gas price, CO_2 tax, and power cost scenarios. The model could also include operation and maintenance expenditures, giving a more realistic representation of the economic situation. With some tweaking of the case study, the usage of HVDC instead of HVAC might also be investigated. This would be quite useful in determining the feasibility of PFS driven offshore electrification all around the world, at all distances.

Another weakness in the model is that the costs of the onshore facility is not included. For future work an investigation of the costs and CO_2 emissions because of the construction of this facility should be done. This will make the results more reliable.

A model that takes the variations of gas, oil and power price, CO_2 tax into account, alongside with the costs of the onshore facility and the maintenance and operations cost would give a clear picture regarding the offshore electrification feasibility on the NCS.

Possibilities for future work can be to compare the PFS and for example offshore wind electrification cases. The investigation of PFS vs. other alternatives could help with the determination of the feasibility of offshore electrification with the use of different power sources.

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Appendix

Calculations base case, no electrification

Equation 1: Annual CO2 emissions from two gas compressors

$$711\ \frac{tons}{day} \times \frac{365\ days}{year} = 259\ 515\ \frac{tons}{year}$$

$$= \ 259\ 515\ tons\ of\ emitted\ CO_2\ annually$$

Equation 2: Annual CO2 emissions from two generators.

$$684\ \frac{tons}{day} \times \frac{365\ days}{year} = 249\ 660\ \frac{tons}{year}$$

$$= \ 249\ 660\ tons\ of\ emitted\ CO_2\ annualy$$

Equation 3: Annual CO2 emissions of each facility with no electrification, base case.

$$= \ 259\ 515\ \frac{tons}{year} + 249\ 660 \frac{tons}{year} = 509\ 175\ \frac{tons}{year}$$

$$= \ 509\ 175\ tons\ of\ emitted\ CO_2\ annualy$$

Equation 4: Total CO2 tax costs for each platform, base case.

$$509\ 175\ \ \frac{tons}{year} \times\ 941\ \frac{NOK}{ton} = 479\ 133\ 675\ \frac{NOK}{year}$$

$$= \ \sim 479\ million\ NOK\ annually$$

Equation 5: Total CO2 tax costs for both platforms, base case.

$$279\ million\ NOK\ +\ 279\ million\ NOK = 558\ million\ NOK$$

Part Electrification – Troll B

Equation 6: Daily income from petroleum production on Troll B.

$$1\ 073\ 295\ \frac{NOK}{day} + 23\ 157\ 120\ \frac{NOK}{day} = 24\ 230\ 415\ \frac{NOK}{day}$$

Equation 7: Annual income from petroleum production on Troll B.

$$24\ 230\ 415\ \frac{NOK}{day} \times \frac{365\ days}{year} = 8\ 844\ 101\ 475\ \frac{NOK}{year}$$

$$= \sim 8{,}84\ billion\ norwegian\ krones\ annualy$$

Equation 8: CO_2 emissions from two GT driven compressors.

$$2 \times 355{,}5\ \frac{tons}{day} \times \frac{365\ days}{year} = 259\ 515\ \frac{tons}{year}$$
$$=\ 259\ 515\ tons\ of\ emitted\ CO_2\ annually$$

Equation 9: Reduced CO_2 emissions on Troll B.

$$509\ 175 \frac{tons}{year}\ - 259\ 515\ \frac{tons}{year}\ = 249\ 660\ \frac{tons}{year}$$
$$=\ 249\ 660\ tons\ saved\ CO_2\ emissions\ annually$$

Equation 10: One-time CO_2 emissions due to production of steel for the electrification module on Troll B.

$$950\ \text{tons}\ \times 1{,}85\ = 1757{,}5\ \text{tons}$$

Equation 11: Annual CO_2 tax costs because of the running compressors.

$$259\ 515 \frac{tons}{year} \times\ 941\ \frac{NOK}{ton} = 244\ 203\ 615\ \frac{NOK}{year}$$
$$=\ \sim 244\ million\ NOK\ annually$$

Equation 12: CO_2 tax costs due to production of steel for the electrification module, Troll B.

$$1757{,}5 \times\ 941\ \frac{NOK}{ton} = 1\ 653\ 807{,}5\ \text{NOK}$$

Equation 13: Power costs for Troll B, including a transmission loss of 9%.

$$33\text{ MWh} \times 42{,}95 \frac{NOK}{MWh} \times 24\text{h} \times 365\text{d} = 12\ 415\ 986\ NOK$$
$$= \ 12{,}42\text{ million NOK annually}$$

Equation 14: Cable cost for Troll B.

$$10{,}869565\ \frac{million\ NOK}{km} \times \ 77\ km \times 0{,}2884 = 241\ 278\ 265\text{NOK}$$
$$= \ 241{,}28\text{ million NOK}$$

Equation 15: Costs of the required amount of steel for the electrification module, Troll B.

$$950\text{ tons } \times 5228 \frac{NOK}{ton} = 4\ 966\ 600\ NOK$$

Equation 16: Total one-time costs for the Troll B platform.

$$241\ 278\ 265\text{NOK} + \ 4\ 966\ 600\ NOK = 246\ 244\ 865\ NOK$$
$$= 246{,}24\text{ million NOK}$$

Full Electrification – Troll C

Equation 17: Daily income from petroleum production on Troll C.

$$1\ 464\ 732 \frac{NOK}{day} + 51\ 408\ 000\ \frac{NOK}{day} = 52\ 872\ 232\ \frac{NOK}{day}$$

Equation 18: Annual income from petroleum production on Troll C.

$$52\ 872\ 232\ \frac{NOK}{day} \times \frac{365\ days}{year} = 19\ 298\ 547\ 180\ \frac{NOK}{year}$$
$$= \sim 19{,}3\ billion\ norwegian\ krones\ annualy$$

Equation 19: Reduced CO_2 emissions on Troll C.

$$509\ 175\ \frac{tons}{year} - 0\ \frac{tons}{year} = \ tons\ of\ 509\ 175\ CO_2\ annually$$

Equation 20: One-time CO_2 emissions due to production of steel for the electrification module on Troll C.

$$650\ \text{tons}\ \times 1{,}85\ = 1202{,}5\ \text{tons}$$

Equation 21: One-time CO_2 emissions due to production of steel for the GIS module on Troll C.

$$106\ \text{tons}\ \times 1{,}85\ = 196{,}1\ \text{tons}$$

Equation 22: One-time CO_2 emissions due to production of steel for the trafo module on Troll C.

$$128\ \ \text{tons}\ \times 1{,}85\ = 236{,}8\ \text{tons}$$

Equation 23: Total one-time CO_2 emissions due to production of steel for the electrification, GIS and trafo modules for Troll C.

$$1202{,}5 + 196{,}1\ \ \text{tons}\ + 236{,}8 = 1635{,}4\ \text{tons}$$

Equation 24: CO_2 tax due to production of steel for the electrification module on Toll C.

$$1202{,}5\ \text{tons}\ \times\ 941\ \frac{NOK}{Ton} = 1\ 131\ 552{,}5\ NOK$$

Equation 25: CO_2 tax due to production of steel for the GIS module on Troll C.

$$196{,}1\ \text{tons}\ \times\ 941\ \ \frac{NOK}{Ton} = 184\ 530{,}1\ NOK$$

Equation 26: CO_2 tax due to production of steel for the trafo module on Troll C.

$$236{,}8\text{tons}\ \times\ 941\ \ \frac{NOK}{Ton} = 222\ 828{,}8\ NOK$$

Equation 27: CO_2 tax costs due to production of steel for the electrification, GIS and trafo module, Troll C.

$$1635{,}4 \text{ tons } \times \ 941 \ \frac{NOK}{Ton} = 1\ 538\ 911{,}4\ NOK$$

Equation 28: Power costs for Troll C, including a transmission loss of 9%.

$$83 \text{ MWh} \times 42{,}95 \frac{NOK}{MWh} \times 24\text{h} \times 365\text{d} = 31\ 570\ 311{,}6\ NOK$$
$$= \ 31{,}57 \text{ million NOK annually}$$

Equation 29: Cable cost for Troll C.

$$10{,}869565 \ \frac{million\ NOK}{km} \times \left(15\ km + (77km \times 0{,}7116)\right) = 758\ 621\ 724 \ \text{ NOK}$$
$$= \ 758{,}62 \text{ million NOK}$$

Equation 30: Costs of the required amount of steel for the electrification module, Troll C.

$$650 \text{ tons } \times 5228 \frac{NOK}{ton} = 3\ 398\ 200 NOK$$

Equation 31: Costs of the required amount of steel for the GIS module, Troll C.

$$106 \text{ tons } \times 5228 \frac{NOK}{ton} = 554\ 168\ NOK$$

Equation 32: Costs of the required amount of steel for the trafo module, Troll C.

$$128 \text{ tons } \times 5228 \frac{NOK}{ton} = 669\ 184\ NOK$$

Equation 33: Total one-time costs for the Troll C platform.

$$758\ 621\ 724 \ \text{ NOK} + 3\ 398\ 200\text{NOK} + \ 554\ 168\text{NOK} \ + 669\ 184 NOK$$
$$= 763\ 243\ 276\ NOK = {\sim}763{,}24\ million\ NOK$$

Calculations – Island mode

Equation 34: Daily CO_2 emissions as a result of island mode for both platforms combined.

$$711\ \frac{tons}{day} + 684\ \frac{tons}{day} + 342\ \frac{tons}{day} = 1737\ \frac{tons}{day}$$

Equation 35: Daily CO_2 tax cost as a result of island mode for both platforms combined.

$$1737\ \frac{tons}{day} \times 941\ \frac{NOK}{ton} = 1\ 634\ 517 \frac{NOK}{day}$$