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Abstract

Equinor is currently considering the development of an offshore wind farm on the Tampen area in the North Sea. The plan is to partly supply the five installations Gullfaks A, B, C and Snorre A and B with renewable energy. This will cut CO_2 emissions by approximately 200 000 tons, and NOx emissions by 1000 tons annually. For this project they have been granted 566 million NOK in support from the Norwegian NOx-fund. Equinor has also applied for Enova support of 2.5 billion NOK.

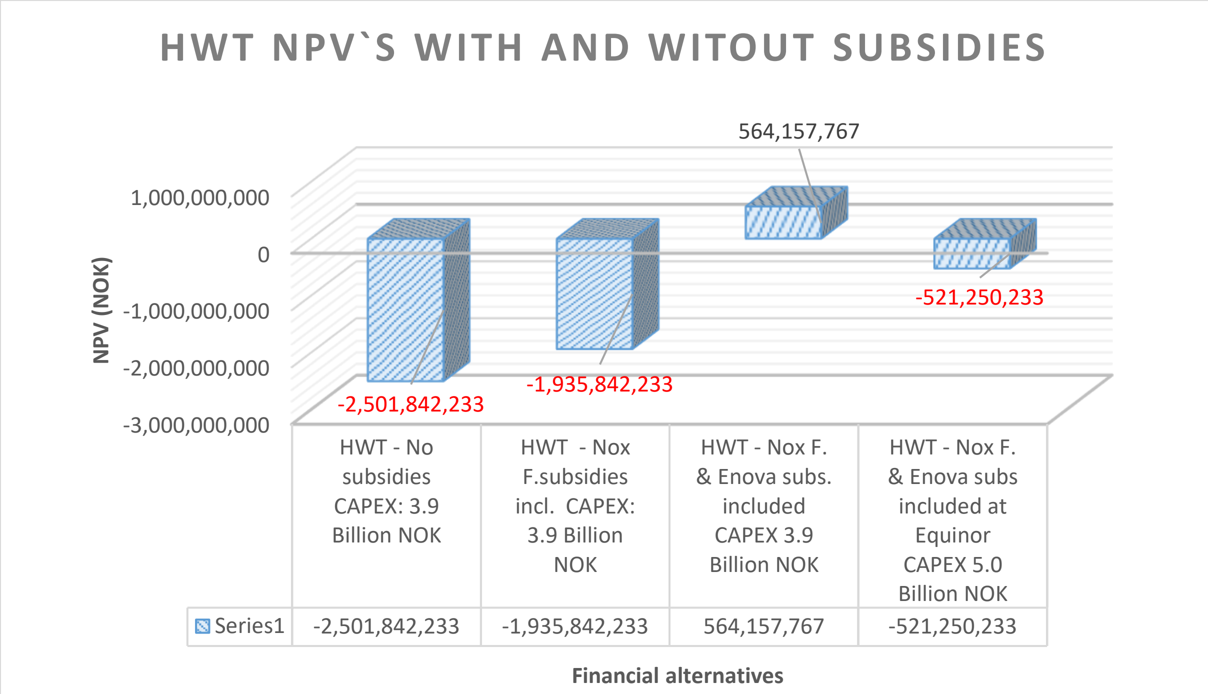
In this thesis the authors attempt to estimate the levelized cost of energy (LCOE) for the current electricity generation by use of gas turbines generators, and the LCOE for the Hywind Tampen wind turbines. Finally, the projects NPV are calculated with and without subsidies.

The authors have developed their own CAPEX and OPEX estimates for Hywind Tampen. Where Equinor is using a CAPEX of NOK 5 billion, the estimate in this paper is NOK 3.9 billion.

Economic models are developed to estimate the LCOE for the current generation of electricity by gas turbine generators. The gas turbine generators themselves, and to a large degree the operation and maintenance of them are sunk costs. They are already built and must be maintained to be ready for the days without wind. The savings for Equinor by setting the HWT project in production will come from selling gas instead of burning it to generate electricity, and from reduced CO_2 and NOx taxes.

The calculations show that from a strict plant economical point of view, it is not recommended to go ahead with the HWT project, because with a 10% discount rate, NPV is negative by 2.5 Billion NOK, without all subsidies. Furthermore, if the HWT project is realized, electricity that currently is generated at NOK 0.77 NOK/ kWh, is replaced by electricity that will be generated at a LCOE of 1.66 NOK /kWh.

When the already granted the subsidies from the NOx fund are taken into the model in year 0, with a 3.9 Billion NOK CAPEX, NPV is still negative at – 1.9 Billion NOK. If also the Enova Subsidies of 2.5 Billion NOK are granted, and taken into the model in year 0, NPV is actually positive by 564 MNOK. At Equinors own CAPEX estimate of 5.0 Billion NOK NPV is again negative at – 521 MNOK.



Should the project be realized, a thorough evaluation regarding the reduced steam generation from Waste Heat Recovery Units is recommended. Our data suggests that if more than 70MW of gas turbine power is replaced by wind power, the platforms may end up with not enough steam for process purposes. It can be an option to scale down to a 70 MW wind park, 9 turbines instead of 11, to avoid problems with reduced steam generation from Waste Heat Recovery Units.

The HWT Project can also partly be seen as a Research and Development investment, or as a marketing cost for Equinor. These kind of positive effects of the HWT project are outside the scope of this thesis. The approach in this thesis are strictly plant economical.

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Abbreviations

AC	Alternating Current
CAPEX	Capital Expenditure
FPSO	Floating Production Storage and Offloading
GFA	Gullfaks A
GFB	Gullfaks C
HAWT	horizontal axis wind turbine
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HWT	Hywind Tampen
IEAE	International Atomic Energy Agency
LCOE	Levelized Cost of Energy
MGO	Marine Gas Oil
MODU	Mobile Offshore Drilling Units
NCS	Norwegian Continental Shelf
NPV	Net Present Value
OPEX	Operational Expenditure
rms	Root mean square
SNA	Snorre A
SNA	Snorre B
SOLD	Simplified One Line Diagram
TLP	Tension-Leg-Platform
VAWT	Vertical Axis Wind Turbine
WHRU	Waste Heat Recovery Unit

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1 Introduction

1.1 Background

Former Statoil's name change in March this year indicated a change in direction for Norden's largest company. From being a pure oil and gas operator, they are now complementing their portfolio with a new business area within renewable energy and low-carbon solutions. With their existing offshore experience and expertise, they have developed their own floating spar concept, Hywind. This concept has been tested with prototypes and small-scale wind parks. Now Equinor is currently considering the development of an offshore wind farm at the Tampen area in the North Sea. By partly substituting the platforms energy supply from gas turbine generators, with energy generated by wind turbines, the plan is to cut CO_2 emissions by approximately 200 000 tons, and NOx emissions by 1000 tons annually. For this project they have been granted 566 million NOK in support from the Norwegian NOx-fund. They have also applied for Enova support for 2.5 billion NOK.

1.2 Problem Background

The target for this thesis is not to answer whether this is a strategically motivated decision for Equinor to position themselves for a future market with ever growing climate pressure, or if there are economic incentives alone. The aim is to analyse this investment from a pure business-economic perspective. This is done by performing a Levelized Cost of Energy analysis and differential cash flow analysis. Data are collected from publicly available documents and through interviews. The interview objects work close on wind projects in one of the largest energy companies in Norway.

Subjects that has been explored in the paper are:

- Current solution for generation of electricity on offshore production platforms.
- Levelized cost of energy (LCOE) for offshore power generation by gas turbines.
- Offshore wind power generation in general.
- Wind conditions in Tampen area
- LCOE for power generation by offshore wind.
- NPV for the Hywind Tampen project.
- Abatement costs.

In this thesis the authors have chosen to look at the problem from a plant-economical point of view. The installation of offshore windmills as an investment decision is considered. There is a large CAPEX investment in year 0 to get the windmills in production. There will also be annual OPEX costs related to the wind turbines. But every year from year 1 to year 20 there are annual OPEX savings mainly from reduced fuel costs, by selling and not burning the natural gas, and reduced CO2 and NOx tax.

1.3 Problem Formulation

What is LCOE in NOK/kWh for offshore power generation by gas turbines? What is LCOE for offshore power generation for offshore power generation from Hywind Tampen (HWT) ?

Will the net present value (NPV) still be negative when annual OPEX savings from reduced fuel costs are accounted for?

What are the abatement costs for this project?

Figure 1: Tampen illustration. Source: Equinor

1.4 Klimakur 2020

Klimakur 2020 is the name of an agency group established by the Norwegian Ministry of Climate and Environment to explore means for reduction of greenhouse gas emissions [1]. The background for the establishment of the agency is that Norwegian gas emissions, as stated in the Climate Agreement, has to be reduced by 15 to 17 million ton CO_2-equivalents by 2020. A large share of Norwegian emissions are rooted in the oil industry and the Norwegian Petroleum Directorate has been a central player in Klimakur 2020. In 2010, Klimakur released a report where different measures for CO_2-reduction were presented, among those offshore wind power. The conclusion at the point was that there is a great challenge involved in providing offshore installations with stable/continuous energy from offshore wind parks.

1.5 EU ETS

Norway is bound by the EU emissions trading system (EU ETS). This means that EU's emission trading system with its provisions and obligations applies to Norwegian obligated businesses at the same level as EU's obligated business. About fifty per cent of Norway's carbon emissions are bounded by the system, which cover both land based industry, petroleum industry as well as aviation. The Norwegian Environment Agency is responsible for permissions for quota obligated emissions, measurements and reporting of emissions, allocation of quotas and settlement of quota obligations. Annually, obligated businesses must hand in the same number of climate quotas as tons CO2 equivalents emitted [2].

Yearly CO2-compensation is calculated by multiplying the business' foundation for compensation with European Union Allowance (EUA) forward price and annual support intensity. EUA forward price shall equal the average of daily closing prices the year before the support year at EUA forward contracts with delivery December previous year. Since the petroleum industry is bound by the trading system, it is in their interest to reduce their share of CO2 emissions. This will be considered in the economic analysis as an expense for gas turbines. The previous years' EUA forward price are listed below. The price for 2018 will be used for this thesis.

Table 1: Table listing average prices for quotas in recent years, 2013-2018 [2]

Year	2013	2014	2015	2016	2017	2018
Price of quota (NOK)	59.27	36.6	51.68	79.02	50.25	54.91

In July 2018 a new act in the agreement was put in to action in the EØS agreement. This is the establishment and operation of a reserve of quotas for market stability. In the period from 2019 to 2023, 24 per cent of the surplus of quotas are put in spare. From 2024 the deposits will return to 12 per cent again. From 2023 the part of the market stability reserve which exceeded the number of quotas auctioned the previous year, will be permanently deleted. These means are steps towards a more aggressive and ambitious work towards reducing emissions. This will probably increase the price of a quota in the future and make it more profitable to choose green energy solutions [3].

1.6 Case study: Tampen-area

The Tampen area is a gathering of oil- and gas fields with their belonging infrastructure at the Norwegian continental shelf. It is not strictly defined geographically, but consists among other of the fields Snorre, Statfjord, Gullfaks and Kvitebjørn. All the Norwegian fields at the area are operated by Equinor [4].

The Tampen area has a water depth from 130-140 metres and is located 160 km from Mongstad. The concept Equinor has chosen for the wind farm is a grid of 11 spar-buoy wind turbines each with an individual capacity of 8 MW. The Spar-Buoy is a cylindrical structure stabilized using ballast. With a heavy sub-structure and a lighter upper structure, the buoy's centre of gravity lies beneath its centre of buoyancy which results in a stable structure. The turbine model chosen is the Siemens SQT. 8.0-154, with a hub height of 95 metres. This is a 3-bladed turbine and as the name suggests, the blade diameter is 154 m. The nacelle weight is 480 t and the floater weight 10 000 t. Siemens have not shared the power curve for their model, instead the power curve from Vesta's V164-8.0 MW turbine is used. Data for both Siemens and Vestas are listed in the table below.

Table 2: Turbine data for Siemens and Vestas

TURBINE DATA	Siemens	Vestas	
D	154	164	m
A	18627	21124	m^2
Cut-in wind speed	3-5	4	m/s
Nominal power at	13-15	13	m/s
Cut-out	25	25	m/s
Maximum 3s gust	70	-	m/s
Nominal power	8000000	8000000	W

The Hywind Tampen floating wind farm will provide Gullfaks A, B and C and Snorre A and B with electricity. The wind turbines are expected to meet about 35 % of the annual power demand. Equinor themselves have estimated the capital expenditures to reach NOK 5 billion, where the NOx fund has committed to provide up to 566 million NOK in investment support. [5]

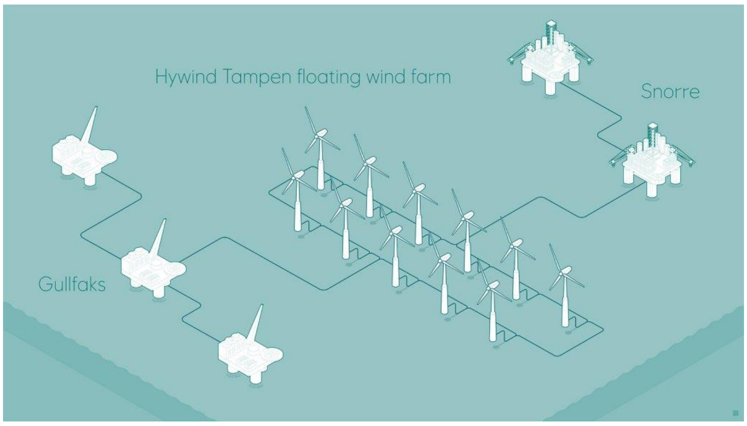

Figure 2: Outline of the Tampen field [5]

Gullfaks can be seen as a collective power system with regards to wind power integration. There are power stations at Gullfaks A and C, where Gullfaks A has installed 4 gas turbines for electrical power production of the type LM2500, yielding 22 MW, while Gullfaks C has 3 such turbines. Gullfaks A and C are connected by a sea cable with 20 MW transfer capacity. Gullfaks A provides Gullfaks B with main power by 2 sea cables with a total transfer capacity of 20 MW. Heat recovery systems for power stations on both Gullfaks A and C is installed, covering a heat demand of 40 MW. Towards 2019 a power demand for electrical driven operations will average around 19 MW [6].

Snorre B has the most energy efficient power generation at the Tampen area through a combined power station where two gas turbines of the type GE LM 2500+ delivers through steam through a steam boiler to a 15 MW heat recovery steam generator (HRSG).

Distance between Snorre B and Gullfaks C is approximately 35 km. For power transmission between the wind park and the two fields a 22 MW cable is used.

Data collected from Gullfaks C also shows good wind resources at the site. The wind speeds are measured on 80 m, not far below the hub height at 100 m. The dominant wind the direction is from south where the data shows wind speeds up to 25 m/s, see wind rose below. The wind speeds have been measured 4 times each 24-hour for 10 years, from 2008-2017

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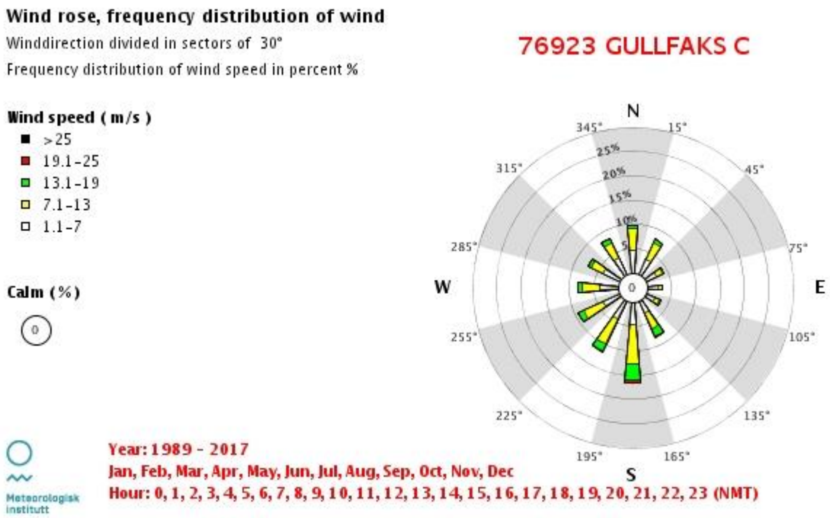


Figure 3: Wind rose, frequency distribution of wind. This model shows the distribution of wind velocities, speed and direction. The distribution is based upon measurements from 1989-2017 measured at 80 meter altitude on the Gullfaks C installation. The data is collected from Meteorologisk Institutt's website eKlima.

2 Method

This assignment will be partially based on qualitative research with interviews as method for data collection. And partly literature review and development of economic models, and wind models based on gathered data. In short the method has been as follows:

- **Information gathering:** Wind data, gas production and gas consumption data. Performance data for gas turbines with regards to emissions and fuel consumption.
- **Qualitative interviews:** To gain understanding of current operation of gas turbine generators, and current available technology and performance of wind turbines.
- **Development of models:** Development of wind model to calculate annual output for HWT. And development of models for LCOE for HWT and LCOE for current generation of electricity by gas tubine generators. Finally development of NPV Model for the project as a whole.

2.1 Information gathering

In development projects where project stakeholders and manufacturers are often unwilling to divulge, it can be difficult to get proper information and reliable numbers. Specially in projects with political anchorage and lobbyists with contradicting opinions, note green energy projects. The debate on whether gas turbines, onshore grid electricity or wind turbines are the best way to supply an oil rig with energy, is no different. This thesis does not try to answer whether one or the other is the sosio-economic best solution, but rather the best solution from a business economic perspective. Care has therefore been taken while choosing sources of information and for data collection, where "neutral" sources have been favoured.

Apart from available resources and literature, information has also been acquired through interviews. The interview objects have been anonymised to preserve their integrity both when the results are analysed and presented.

Most of the cost elements are results of studies still at an early stage, and all of the cost elements associated with the study are therefore affected with a great deal of uncertainty. A "top-down" estimation technique, based on comparison with earlier known cost data for installations are used. Wind turbine and gas turbine specifications are collected from the manufacturer. The wind turbine supplier for Tampen has not yet been released, but there are several manufacturers with 8 MW turbines. They all have more or less similar data, and these will be used as reference for best available technology. Power curve and other information not available from the manufacturer, are collected from "Description of an 8 MW reference wind turbine" [7] and Vestas V164-8.0 MW turbine.

To develop the model for current generation of electricity on the Snorre and Gullfaks platforms a spreadsheet published in 2013 on the pages of the Norwegian petroleum directorate has been important. It is called "oversikt over motorer og turbiner" [8] and lists all the discharge points of CO2 and NOx gases in 2013. The amount of electricity needed of course varies with time, both from 2013 until now, and from now and until 2042. For this reason all costs related to fuelgas, CO2 taxes, NOx taxes, and CO2 Quotas has been calculated in NOK/kWh. So, when calculating the fuel related savings related to shutting down gas turbine generators the authors has just used the annual estimated amount of Hywind tampen generated power and multiplied this with current costs in NOK/kWh. And then you have the annual savings. Finally it will be discounted in the NPV model.

Weather data at Tampen are collected from Norwegian Meteorological institute at eklima.met.no. eKlima is a free and open web portal where everyone can access. eKlima contains weather data from all weather stations currently and previously run by Norwegian Meteorological institute. eKlima provides simple lists, statistics and sophisticated analysis, based on preferences. The perk is the amount of data collected at offshore fields, not at least at high altitudes. Relevant data for this thesis are collected from Gullfaks C. Gullfaks is located right at the centre of analysis for this thesis and the weather data are collected from 80 m altitude. The wind speed will be evaluated at relevant height by doing a vertical extrapolation of the measured data.

2.2 Qualitative interviews

As opposed to quantitative methods where the target is to measure the extensive number related to a phenomena, the qualitative methods seeks to establish an understanding of in this case, the technological phenomena based on non-numerical data. [9]. Because development of floating wind farms is at an early stage, as well as grid integration at oil fields, a quantitative approach is for some parts of the thesis a useful way of collecting data.

The qualitative interview can be characterized as a conversation with a specific target between the interviewer and the informant. The main goal with these interviews is to get an aspect of challenges and costs related to implementation and operation of wind farms in offshore oil fields. The use of interviews within research creates a set of data that would not exist without active participation from the researcher [10].

This is in contrast to other research methods like observation or mathematical analysis, where one deal with material that exists regardless of the researchers involvement. However, because scientific results does not present itself on its own, they will never be completely unaffected by the researcher. This can explain the widely differing results when it comes to economical calculations for green energy efforts. The researcher is self a part of the social life and cannot be completely free from pre-assumptions [10].

2.3 Semi-structural interviews

Qualitative interviews can be carried out with different levels of structure. The qualitative study in this thesis is based on semi-structural interviews. This can be best described as a conversation between the researcher and the respondent, led by the researcher. The interviewer follows a guideline where the majority of the questions and topics are set in advance, but also provides flexibility for both the interviewer and informant to elaborate on topics that are relevant and interesting. This requires some thoughtful planning.

This type of interview makes it easier to make comparisons between the correspondents, contrary to open interviews. Despite not being totally open, the semi-structural interview has some flexibility, and the data that is being produced during a session can lay the foundation for the rest of the interview [9].

A structural interview offers an opportunity to interpret the context of what is being told, and catch a better understanding of what level of meaning the informant puts in the response. In a structured interview, you will only get answers for the questions you ask, and relevant questions can be difficult to come up with when touching new areas. In a semi-structured interview, the informant can help with that and thus reveal new things as the sessions goes by. As a result, the researcher can get more nuanced and deeper knowledge of specific themes. As the interview-objects in this thesis are chosen for their expertise in certain areas or hands on experience with projects, this is an ideal way to take advantage of their knowledge.

In short, the semi-structural interview gives reliable, comparable qualitative data, while at the same time provide an opportunity to identify new ways of learning and interpreting the topic at hand.

3 Theory

3.1 Levelized cost of energy

To make an informed decision whether to proceed with large scale offshore wind parks it is crucial to consider all the lifetime costs from preliminary research to shut down and decommissioning. A Levelized Cost of Energy (LCOE) is one of several tools for calculating cost efficiency in climate analysis. The key concept of an LCOE is to measure the costs over a lifetime and divide by total energy production. It is an economic assessment of the net present value of a unit-cost of electricity, NOK/kWh. To calculate LCOE key inputs are capital and financing costs, fixed and variable operations maintenance costs, fuel costs, and an assumed utilization rate for the different plan types.

Levelized Cost of Energy is used to compare different electricity generation technologies on a consistent basis. [11]

The total lifetime costs can be expressed by the following equation [12] [13]:

$$\left(\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}\right) \tag{2.1a}$$

and the total lifetime output as (II)

$$\left(\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}\right) \tag{2.1b}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.1}$$

Where I_t = initial investment costs and expenditures in year t, including financing. M_t = expenditures related to O&M in year t, F_t = fuel expenditures for the year t, E_t =total electric output for year t, r = discount rate and n = the power site's expected lifetime. **Error! Reference source not found.** below illustrates some of the factors that may be considered for a LCOE calculation.

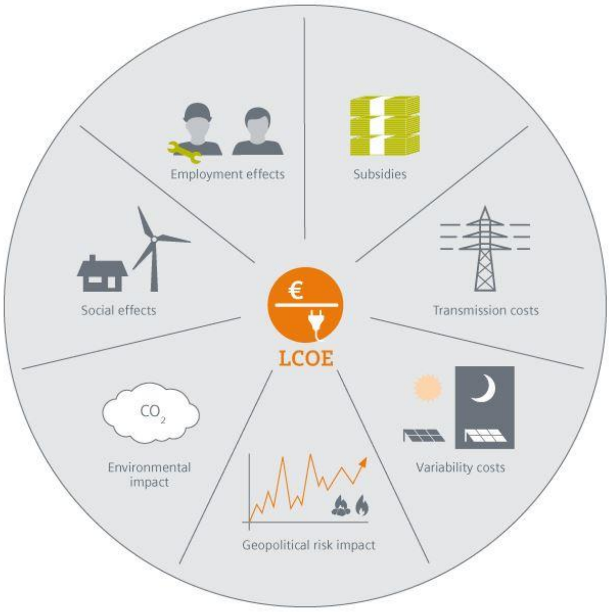


Figure 4: The figure illustrates factors affecting LCOE calculations. The figure is taken from Siemens' "What is the real cost of offshore wind?" [14].

Employment effects. This assignment will mainly focus on operational economic considerations where measurable quantities can be obtained. Employment effects will not be considered in this LCOE-analysis because it is too difficult to estimate the economic impact this will have.

The economic effects of environmental impact will be taken into consideration only in the sense of CO_2- and NO_x-taxes. The number of CO_2-equivalents will be accounted for in the LCOE-calculation as an increase or reduction in taxes. It is hard to tell how this will affect the cost over a lifetime as the prices are market-driven and volatile.

Because the amount of power delivered from the turbine increases with the cube of the wind speed the electrical output varies a lot. There is a cost related to this uncertainty. This means that the gas turbines must run with variable speed or lower capacity, which results in lower efficiency and an increase in NO_x- and CO_2-emissions.

Subsidies from the NO_x-fund and Enova are considered in this analysis. LCOE is calculated both with and without subsidies.

3.2 Differential cash flow

The LCOE is a useful tool for comparing different energy alternatives. Because the gas turbines at Tampen is a sunk cost, already available and in use at the installations, they cannot be compared with a new wind park. A useful tool for making investment decisions regarding new projects is the differential cash flow. In short, this is a NPV-analysis considering the gain received from taking on a new project. A positive incremental cash flow results in an increase in operating income, whereas a negative incremental cash flow results in a decrease. A company is indifferent on whether to proceed or shelve a project when the net present value equals zero.

In this thesis, the differential cash flow from building a wind park for energy purposes is calculated. This is compared to the existing situation where the energy demand is covered by gas turbines.

3.3 Abatement costs

Abatement costs is, along with NPV analysis, one of two methods used for economic calculations within climate analysis. The abatement cost is easy to compare with the price of a CO_2-quota, and it is easy to compare the cost of different climate related efforts through the method. For that reason it has been established as a standard for environmental cost calculations [15]. Like other NPV analyses, a company is indifferent when the NPV of the earnings related to CO_2 reduction (left side of following equation) equals the cost of the measure done to reduce CO_2 (right side of the following equation). This can be expressed with the following formula:

$$\sum_{i=0}^{T} \frac{1}{(1+r)^2} v_t X_t = \sum_{i=0}^{T} \frac{1}{(1+r)^t} (I_t + C_t) \qquad (3.1a)$$

Where $X_t$is ton CO_2 in year t and v_t is the price or value of CO_2-reduction in year t, I_t is the investment and C_t is operation costs in year t. If the price/value of CO_2-reduction is assumed constant over time (in real value), we can divide with the net present value of the CO_2-ton quantity on both sides and get:

$$v = \frac{\sum_{i=0}^{T} \frac{(I_t + C_t)}{(1+r)^t}}{\sum_{i=0}^{T} \frac{X_t}{(1+r)^2}} \qquad (3.2b)$$

NPV of costs divided by NPV of saved CO_2 emissions gives the expression for abatement costs. This is the formula used for calculating abatement costs in this thesis.

3.4 Energy demand at an offshore field

An offshore unit for production of hydrocarbons, regardless of type has a certain need for energy to operate. The north sea can be a cold and hostile environment. Energy is needed for lighting and illumination, heating for the accommodation spaces for 2-300 personnel that needs all the basic facilities of a medium sized hotel. In addition to this there are all the computer systems and other control systems used for controlling the platform and keep contact with the outside world.

The single largest power consumer, however, is the production process. According to interview object number 2, at operator company number 1 approximately 70% of the electrical power generated onboard is distributed to the production process consumers. The same thing is apparent when categorizing the main consumers on the Snorre B platform. For the Snorre B platform approximately 67% of max capacity is distributed to the production process:

Table 3: An overview of electric power consumers on Snorre B, derived from SOLD Snorre B [16].

Types of Consumers		
	(MW)	in %
Accomodation	1.2	2.1
EMCY Syst	5.4	9.1
Process	40.4	67.2
Drilling	13.1	21.7
Total active power	60.1	100.0

Approximately 67% of power at max consumption is distributed to Process consumers for the Snorre B main SWBD.

The standard way of power generation offshore has been gas turbines connected to HV 3-phase Synchronous generators, with or without heat recovery system for the exhaust gases. Prior to presenting working principles of gas turbines and generators, some basic theory on electricity and particularly sinusoidal voltage is provided in the following section.

3.4.1 Electrical Energy Needed on an offshore oil & gas production platform

Onboard, the platform electric power is distributed to the following equipment:

Living quarters for personnel:

- Electrical energy for fans, lighting etc.
- Heat needed for warm water and general heating of accommodation.

Vital Systems (Supplied from Emergency Switchboard)

The Production Process

- Electrical energy for operation of machinery
- Heat needed for the production process.

Drilling Module (if the installation has a drilling module)

Position keeping (In case of FPSO thrusters for keeping the bow against the wind):

Below is an example of a Simplified One Line Diagram (SOLD) showing the distribution of electric energy from generators, to main switchboards, transformers, bus breakers and main energy consumers.

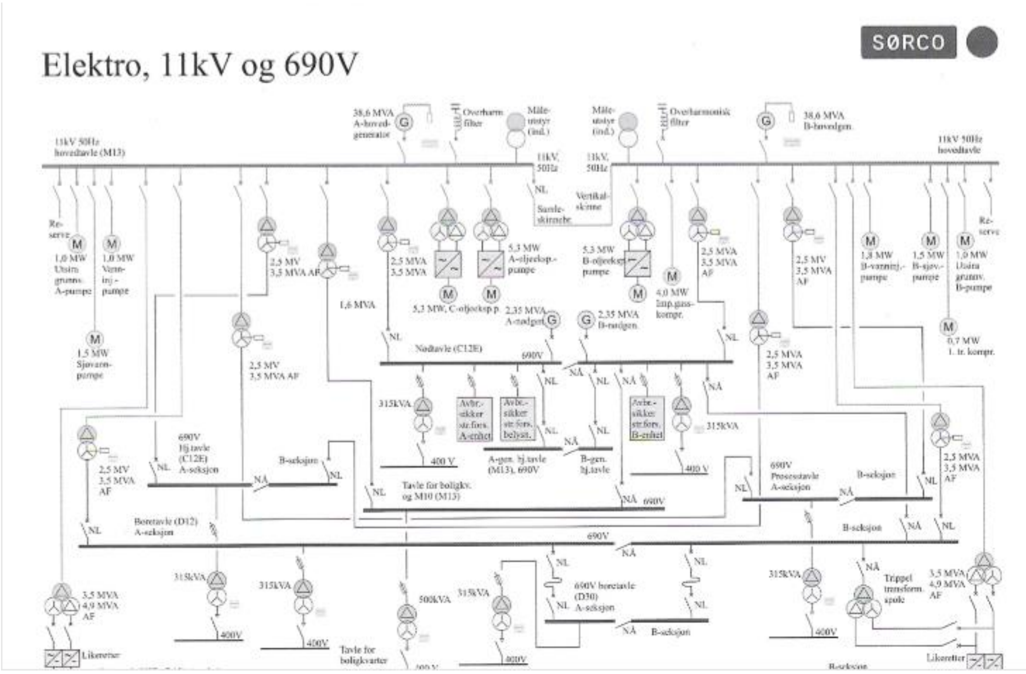


Figure 5: Simplified one line diagram Snorre B [16]

3.4.2 Heat energy needed on oil & gas production platforms

The oil production process has heat demands on several levels. According to interview object number two, at operator company no one, and petroleum technology textbooks [16] the most important are:

- Heating of glycol / mono ethylene glycol (MEG) to heat it up, to dry it out.
- Heating of injection water before stripping oxygen.
- Heating of crude oil to enhance separation.
- Heating of combustion gas for the gas turbines.
- In addition to this heating of ventilation for accommodation and process modules.

All operator companies on NCS have to report annually to various governmental institutions their emissions of NOx. When diesel or gas is burned in either a gas turbine, an engine, in a boiler or in a steam generator NOx are one of the gases emitted. These numbers are gathered on a spreadsheet. By using this spreadsheet, a good and comprehensive overview of all electric power production on NCS, from installations (MODU`s and ships are not covered) is obtained. This is used extensively as a basis for the calculations.

3.5 Basic Explanation of Alternating Current (AC), and relevant SI-Units

When discussing the electric power generation, it is necessary to understand the concept of sinusoidal voltage and the basic SI Units for power.

In the following subchapters, a quick theoretical introduction is provided for AC power and the most important SI-Units needed to describe electric power generation and transmission. This is explained at an understandable level also for non-electrical engineers.

3.5.1 Sinusoidal voltage

As stated in the SOLD above, the type of electrical power generated by the two main generators on the Snorre platform is sinusoidal voltage of 11 kV at a frequency of 50 Hz. This is more commonly known as alternating current (AC). In reality the voltage and current is varying sinusoidally, and for a 50 Hz frequency, the direction changes 50 times within a second.

The sinusoidal voltage is described by the function [17]:

$$v = V cos \omega t \tag{3.2}$$

Where:

v = instantaneous potential difference

V = Maximum potential difference (the voltage amplitude)

Cos = the mathematical cosine function.

ω = the angular frequency (ω=2πf)

f = the frequency = 50 Hz (ω = (2πrad)(50s^-1) = 314 rad/s

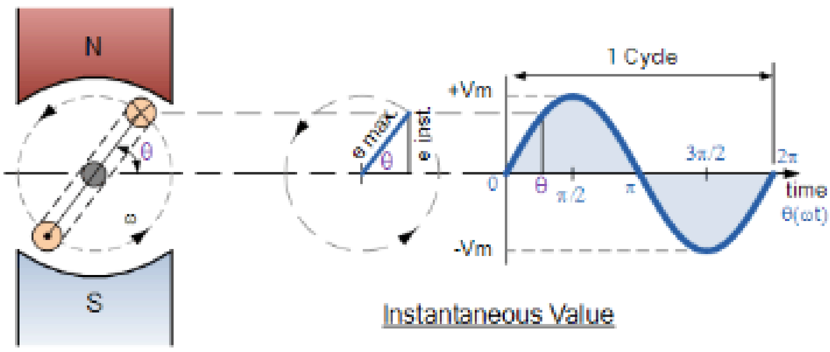


Figure 6: Illustration of the sinusoidal function [18]

AC Power generation and transmission is a complex subject that relatively quickly becomes mathematically complicated. To avoid having to make calculations with equations that is sinusoidally varying with time, electrical engineers use “phasors” and “phasor diagrams”. Phasors are actually rotating vectors diagrams. *“In these diagrams the instantaneous value of a quantity that varies sinusoidally with time is represented by the projection onto a horizontal axis of a vector with a length equal to the amplitude of the quantity”* [17]

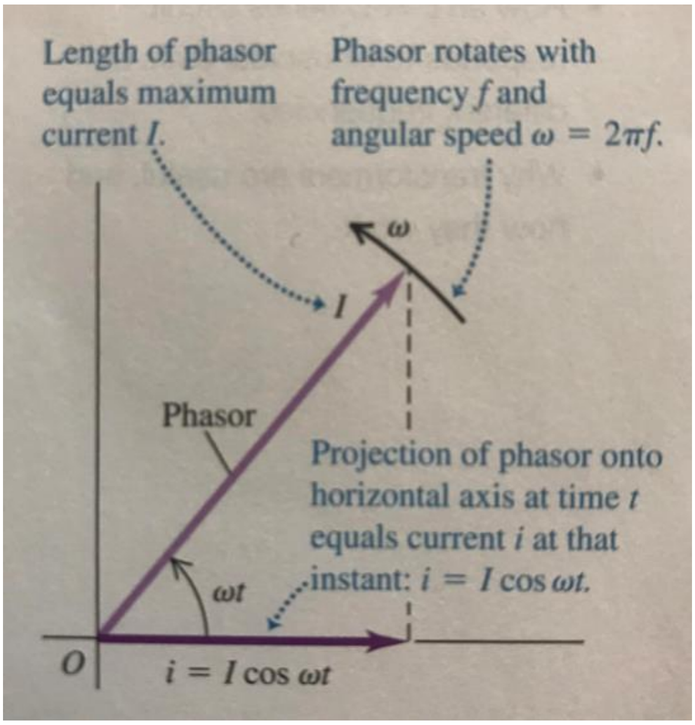


Figure 7: A phasor diagram of the current from Young and Friedman [19]

3.5.2 Root mean square (rms) values

To solve equations with functions where all factors vary with time, is not very time efficient. To avoid having to do complex mathematical calculations, rms values are used. The rms value represents the AC-power quantity equivalent to a direct current quantity at the same voltage. It can be shown that [20]:

$$I_{rms} = \frac{I}{\sqrt{2}} \; and \; V_{rms} = \frac{V}{\sqrt{2}} \qquad (3.3) \; and \; (3.4)$$

Where:
V = the voltage amplitude value, or peak value, of the potential difference.
I = the current amplitude value, or peak value, of the current.

The important thing to know is that when you read 230V on the fuses in your home this is the rms value. Also, when you see 11kV on a one line diagram this is also the rms value. For current and voltages it is normally the rms values that are given, unless specifically stated otherwise.

3.5.3 Power consumers in an electrical circuit

The fact that generators are producing a potential difference varying sinusoidal with time t is established above.

However, no electrical power is transferred until the generator breaker is closed and a circuit is established. The electrical current in ampere (A) also depends on the size and type of load. In AC Circuits there are three main types of power consumers. These are:

- **Resistors (R);** the opposition to flow of current through a resistance in a circuit. Example of resistors are heating elements. Resistance is measured in Ohms **(Ω)**
  For pure resistor in an AC circuit the current and the voltage will vary sinusoidally with time in the same phase at the same frequency. The phasors rotate together in parallel.
- **Inductive Reactance (X_L);** the opposition to flow of current through an inductive element in an AC circuit. Example of inductive elements in AC circuits is AC Motors and coils. Without over explaining we can say that due to a self-induced electromagnetic force (emf), even though both the current and the voltage is varying with time, the voltage phasor is 90° ahead of the current phasor. Inductance is measured in Henry **(H)**
- **Capacitive Reactance (X_C);** the opposition to flow of a current through a capacitive element in an AC Circuit. Example of capacitive element is a capacitor. Again without overexplaining, due to the charging and discharging of the conductive plates in the capacitor, even though both current and voltage is varying sinusoidally with time, the voltage phasor lags -90° behind the current phasor. Capacitance is measured in Farads **(F)**

Impedance (Z): In all larger power grids there will be a mix of resistors, inductors and capacitors. The term for this impedance, which actually is a function of, or the decomposed vector of the R, L and C elements in the circuit.

In practical terms, what is actually done to bring down the reactance, is as to add capacitive reactances (capacitors), to zero out or reduce the effect of the inductive load. This can also be seen from the equation below where XL and XC has different sign.

Reactive power does no electrical work [21].

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad [22] \tag{3.5}$$

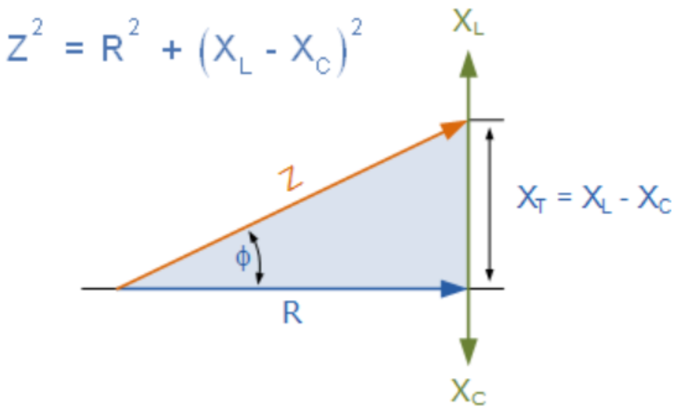


Figure 8: The impedance triangle [18]

3.5.4 Measurement units for Power in AC Circuits

In most AC power circuits, the electrical "load", or power, will come from a mixture of resistors, inductors and capacitors.

This is important when studying electrical drawings like the Snorre SOLD above, or when reading spreadsheets for cables, generators, power consumption and/or production where a mix of MW and MVA is used.

Turbine manufacturers will typically state their specifications in MW, and generator manufacturers will state their specifications in MVA. It is important to be able to distinguish the two. Electrical bills for industrial consumers tend to be in EUR or NOK/MWh, unless the power factor is below a certain limit. Then they will have to pay for reactive power (kVAr) as well. Since reactive power does no work, this is not desired.

The equation for power in an AC Circuit is given by the equation [23]:

$$p = vi = [V\cos(\omega t + \varphi)][I\cos\omega t] \tag{3.6}$$

Which can be reduced to:

$$P_{avg} = V_{rms} I_{rms} \cos\varphi \tag{3.7}$$

Just as what happens for impedances in a AC circuit easily can be described by using high school trigonometry, there is a similar triangle for current, and finally our interest power:

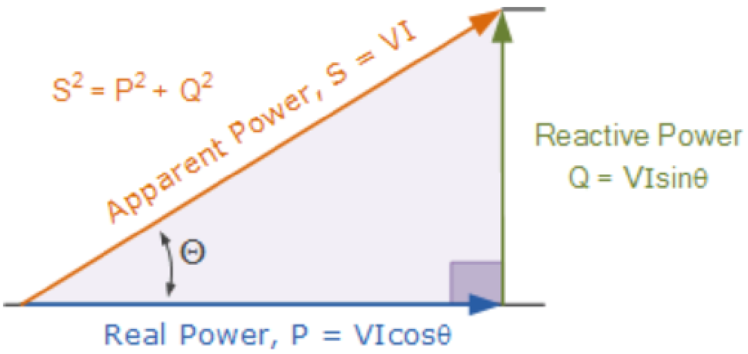


Figure 9: The power triangle [18]

The three types of powers quantities needed to describe AC power generation and transmission:

- **Active power (P);** measured in watts or in this case Megawatt. (MW) This is the quantity that does the actual electrical work. And furthermore, this is what determines the physical dimensions of the wind turbine shaft or gas turbine output shaft. Hence gas turbine manufactures, or wind turbine manufactures will state the output of their machines in MW.
- **Reactive power (Q);** measured in volt-ampere reactive (Var), or in this case. (MVAr) In layman's words this is called "blind-power" or more correctly reactive power. This power does not carry out any electrical work. But it is there, and generators, cables and other electrical machinery have to be dimensioned to withstand the heat load from both active and reactive currents.
- **Apparent Power (S);** Is the vector sum of the active power vector (P), and the reactive power (Q)- The magnitude is measured in volt-Ampere, or in this case. (MVA) When generator manufacturers state specifications they tend to do it in MVA.

Power factor, or cos ϕ: As one can see from the power triangle above, if the Active Power demanded and the power factor is known, one can easily calculate the apparent power and vice versa ($P = S\ cos\ \varphi$). In many power grids cos ϕ has a value from 0.8 – 0.9. Higher is more efficient than lower. In a setting with many inductive consumers (motors etc.), and too low capacitive load, a situation may arise where the generator reaches maximum current, while the prime mover, the gas turbine or the wind turbine, still has not reached maximum output. Data for Snorre B suggests a power factor of 0.78.

3.6 Gas turbines

3.6.1 General information about gas turbines

Various scientists have experimented with gas and steam turbines for hundreds of years. Steam turbines and gas turbines have many similarities. The main difference being the working media, and where the combustion of hydrocarbons take place. In steam turbines the working media is water, and in gas turbines the working media is air. In a steam cycle the combustion takes place in an external boiler, while in a gas turbine the combustion takes place within the gas turbine. Very often for large scale onshore power production by usage of natural gas, steam turbines and gas turbines are used in a combined cycle.

Apart from working media and where the combustion takes place there are many similarities. Examples of gas and steam turbines throughout time are Hero`s aeolipile in year 50 AD, Leonardo Da Vinci's Chimney Jack in 1500, to Sir Charles Parsons steam propelled ship in 1894 and Charles Gordon Curtis first patented gas turbine in the US in 1899. However, it was not until 1903 the first gas turbine that produced more power than it needed to run its own parts, was created. [24]

The first turbine made that produced net power was invented by the Norwegian engineer Ægidius Elling in Oslo 1903. [25]

Today the use of gas turbines as the prime mover for electric generators, ship propellers, aircraft engines and large compressors is widespread. Modern society is hardly possible without gas turbines, and certainly not the aviation sector.

According to IEAE, in the year 2017, 23.1% of the world's electricity production originated from the combustion of natural gas [26]. The two most common ways to covert natural gas to electrical energy is through use of a boiler and steam turbine, or gas turbine, or a combined cycle. It is also possible to burn gas in a medium speed 4 stroke gas reciprocating diesel engine, but this is not very common due to high OPEX costs for diesel engines.

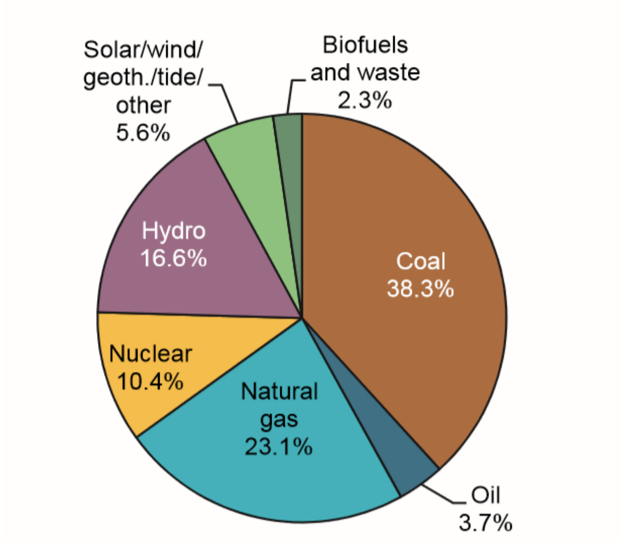


Figure 10: World gross electricity production, by source, 2016. [27]

According to Jahnson [28] “Overall, it can be seen from Fig. 1.1 that gas turbines play, or will play, an important role in the sectors, responsible for about 50% of the total worldwide CO emissions”. The sun and wind do not deliver a constant output, but a varying quantity of power depending on the weather. Most industries and private power consumers need a stable power supply, and until technology evolves, a key factor to reduce the CO2 emissions will be to get an optimal co-existence of both gas-turbines and wind turbines on the same power grid. This applies in the case of Hywind Tampen, in addition to the European, or for that sake the world’s power grid.

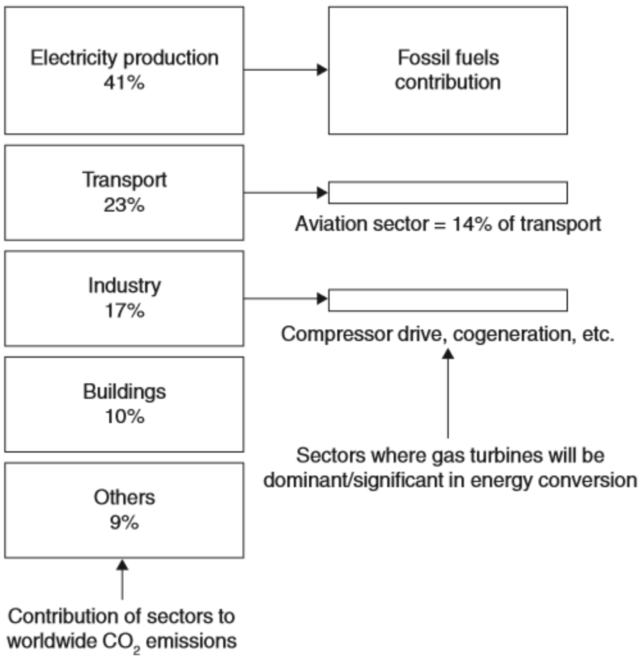


Figure 11: Sources of worldwide CO_2 emissions and potential of gas turbines [28]

3.6.2 Gas turbine working principle

There are many different types of gas turbines. The working principles are more or less the same, with a few smaller differences.

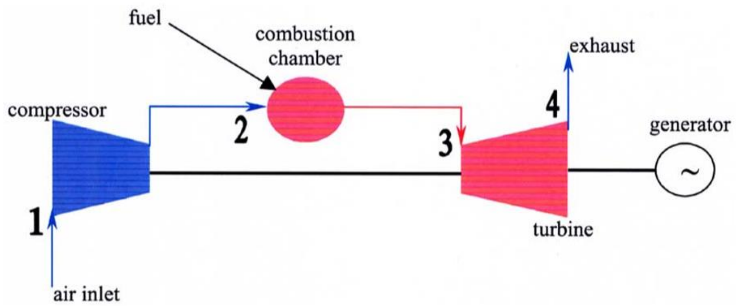


Figure 12: Simple cycle gas turbine [29]

1. Air is drawn in to a centrifugal compressor in the first stage. The air is compressed. When air is compressed three things happen.
   - The air gets warmer. The temperature (T) increases
   - The volume decreases (the air gets compressed)
   - Both of the above contributes to that the energy content of the flowing mass increases. We say that the enthalpy increases.

2. In second stage, in the combustion chamber gas or diesel is burned. This gives an additional increase in temperature.
   - The air gets warmer and is mixed with the exhaust.
   - The internal energy of the working media increases.
   - The pressure is kept constant during combustion, but the volume of the working media expands.

3. In the third stage the working media is expanded through the high-pressure (HP) turbine.
   - The expanding working media drives the high-pressure turbine.
   - Heat and pressure energy is converted to rotating shaft energy.
   - The internal energy of the working media is decreasing.
   - When the working media is discharged from the gas turbine it still holds a relatively high temperature

4. The Electrical generator is connected to the outlet shaft from the Turbine.

3.6.3 Definitions and relevant units

When reading about the theoretical basis for gas turbines, the Jules Brayton cycle, one will relatively quickly encounter various diagrams, quantities and measures. The p,V diagram is quite straight forward and easy to understand, this is pressure and specific volume (m^3/kg) plotted together. This is comprehensible for most people with basic physical knowledge. The other diagram that usually appears in context of the Jules Brayton cycle is the T,s diagram. T is temperature on the y-axes, on the x-axis we have Entropy (s), which is not that obvious.

3.6.3.1 Entropy

Entropy is classically defined as "a quantitative measure of the disorder of a system" [30]. This definition does not help too much in day to day calculations of power systems. A vaguer, yet more intuitive explanation, is this one; the definition of entropy can be derived from the second law of thermodynamics which when applied to heat engines is stated: "It is impossible to construct an engine which, when operated in a cycle, produces no effect except to do work and exchange heat with a single reservoir" [31]. This is also vague, but we get the notion that it has to do with energy quality and efficiency losses at transformations. The mathematical definition does not provide any more immediate insight and is as follows [31]:

$$dS = \frac{dQ}{T} \qquad (3.8)$$

Where:
dQ: is an infinitesimal (very small) transfer of heat
T: absolute temperature in degrees Kelvin (K)

One explanation of entropy that gives much insight is the one of Oxford University Physics master's degree holder Steve Mould who makes a living as a science presenter. He states firstly that "it is not heat that you need to run an engine, it is a difference in temperature" [32]. And finally, what we are looking for, Steve Mould preferred explanation of entropy: "Entropy is a measure of how spread out your energy is" [32]. Mr Mould continues to explain that "Entropy always increases" [32], and "energy is only useful when it is clumped together." [32]. These things together give meaning to our preferred definition of entropy: "Entropy is a measure of how spread out your energy is" [32].

The unit of measure for entropy is $\frac{J}{K}$ or more commonly and for the change in entropy dS is $\frac{kJ}{K}$

3.6.3.2 Isentropic process

"A process during which the entropy remains constant is called an isentropic process" [33] This is an idealized process that is not possible to obtain in practice, but acts as a model which is compared to real machines and processes to get as close to $\Delta s = 0$ as possible.

3.6.3.3 Enthalpy

It is much easier to define enthalpy than entropy. Enthalpy, often denoted (h) and measured in $\frac{J}{kg}$ or more common $\frac{kJ}{kg}$ is the sum of the internal energy of the substance plus the product of the specific volume (V) and the pressure (P) [34]:

$$h = u + Pv \tag{3.9}$$

3.6.3.4 Specific heat capacity

How much energy that is required to raise the temperature of one substance 1K depends not only on which substance we are, heating. But also on which process that are used to heat up the substance, and on the temperature.

In order to perform gas turbine calculations defined by the joules brayton process we need to know

c_v: Specific heat capacity at constant volume. Given in (kJ/kgK) [35]
c_p: Specific heat capacity at constant pressure. Given in (kJ/kgK) [35]

3.6.4 Thermal efficiency of a Gas Turbine

As indicated above, to be able to look at the thermal efficiency of the Joules Brayton process a good help is to study the process in Ts and pV diagrams. The goal is to understand what affects the efficiency of the gas turbines, so that one does not end up decreasing the thermal efficiency when changing the power production system of Tampen area by introducing new wind turbines and thus changing the load of each generator in the system.

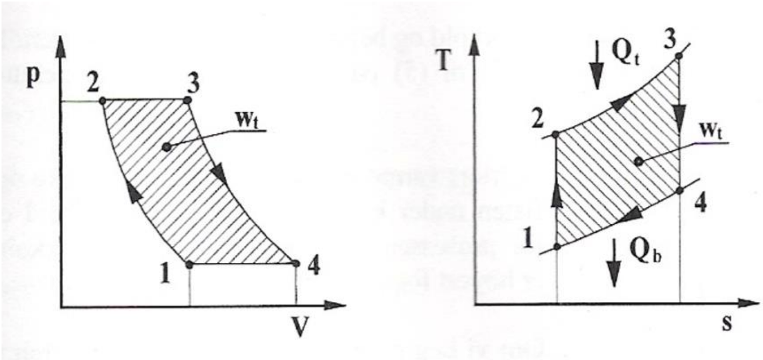


Figure 13: Brayton process [35]

According to A.Lund the thermal efficiency of a gas turbine is as follows [35]

$$\eta_t = \frac{w_t}{q_{tilf}} = \frac{Net\ technical\ work}{added\ heat\ energy} \tag{3.10}$$

And more specificall

$$\eta_t = 1 - \frac{Q_b}{Q_t} = 1 - \frac{h_4 - h_1}{h_3 - h_2} = 1 - \frac{c_p\,(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{3.11}$$

If an ideal gas is assumed, and a constant c_p , we can see that the thermal efficiency increases with increasing turbine inlet temperature T_3, and lower heat rejection temperature to heat zink T_4. Or in other word take as much as possible energy out of the working media before it leaves the turbine, and waste heat recovery unit (if mounted).

η_t: *Thermal efficiency of the gas turbine*
w_t : *Net technical work*
q_{tilf}: *added heat energy*
h_n: *entalphy at the various stages*

Net Technical work (w_t), and the connection to heat can be expressed as follows: [35]

$$w_t = w_{tT} - w_{tK} = \Delta_{hT} - \Delta_{hk} = c_p = \left((T_3 - T_4) - (T_2 - T_1)\right) \tag{3.12}$$

Where
w_{tT}: *the turbine work*
w_{tK}: *the compressor work*

Furthermore, the added heat (q_t) and removed (q_b) heat is defined as follows [35]:

$$\text{Added heat: } q_t = c_p * (T_3 - T_2) \tag{3.13}$$

$$\text{Abducted heat: } q_b = c_p * (T_4 - T_1) \tag{3.14}$$

3.6.5 U.S. Customary Units vs SI units and Heat rate

In the SI system the unit for energy is joule (J) or Joules / second (J/s) which is the same as watt (w). While in the U.S. Customary units one British Thermal Unit (Btu) is "the quantity of heat required to raise the temperature of 1 pound of liquid water by 1 degree Fahrenheit at the temperature at which water has its greatest density (approximately 39 degrees Fahrenheit)." [36]

Conversion factor from Btu/kwh to kJ/kwh is 1,055.

The unit used volumetric measurement for gas in Norway is Standard Cubic Meter (Sm^3). A Sm^3 of gas is 1 m^3 of the substance at 15°C and pressure 1.01325 Bar [37]. For conversion between Sm^3 and BTU we use the relationships from APPENDIX 4, found on the pages of the Norwegian petroleum directorate. [38] (1 cubic foot = 1000 BTU – 1 Sm^3 gas = 35.314 cubic feet) → Conversion from Btu to Sm^3 = 1/35314)

$$1\, Sm^3 = 35.314\, cubic\, feet \qquad [1\, cubic\, foot = 1{,}000\, Btu]$$

$$1\, Sm^3 = 35.314\, [1000\, Btu]$$

$$1\, Sm^3 = 35.314\, BTU$$

$$BTU = \frac{1\, Sm^3}{35.314}$$

Be aware that in the SI System the Prefix M = 10^6, in this paper when we write MBtu this means one million Btu. Occasionally in other literature you may find the unit MMBtu. In which case they also mean one million BTU. This is originated from the old roman number M which is 1000. So when following this analogy MMBtu is a 1,000 1,000 Btu. In other words one million. But for the rest of these thesis in the text produced by the authors MBtu is one million Btu, as outlined in the International System of Units.

In the previous subchapter the term "thermal efficiency" η_t was explained, which is a number between 0 and 1, where higher number is more efficient than lower.

Another expression that is much used to describe the efficiency of gas turbines is Heat rate, which is "The fuel consumption of a gas turbine divided by the output" …"generally expressed as Btu/kWh" [39]

$$\text{Heat Rate} = \frac{Thermal\ Energy\ in\ (Btu)}{Electrical\ Energy\ out\ (kwh)} \tag{3.15}$$

Sometimes efficiencies is given in %, sometimes as heat rate. It is very useful to be able to convert from efficiency factor to heat rate and back. As seen above:

$$\eta_t = \frac{w_t}{q_{tilf}} = \frac{Net\ technical\ work}{added\ heat\ energy} \tag{3.16}$$

When knowing that

$$1\ kWh = 3.6\ MJ = 3412\ Btu$$

Heat rate is the inverse of efficiency so if it is needed to convert heat rate to efficiency simply divide 3412 by the heat rate. To convert from efficiency to heat rate, perform the inverse operation. For example:

The LM 2500+ gas turbines on Snorre B has a given real thermal efficiency factor of 45.8 % [8] To perform calculations with natural gas as fuel it is easier to use heat rate:

$$Heat\ rate = \frac{3412}{0.458} = 7449.78\ \frac{Btu}{kWh}$$

3.6.6 The General Electric LM 2500+ Gas turbine

The GE LM 2500 gas turbine are a type of turbine called aeroderivative turbines, this is "an aircraft jet engine modified for ground applications to produce shaft power instead of thrust." [40]. These turbines consist of a compressor and high-pressure turbine on the same shaft, and a low-pressure power turbine on a separate shaft where the generators is connected.

Relevant for our study is that the production platform Snorre B is equipped with LM 2500 + turbines for power production.

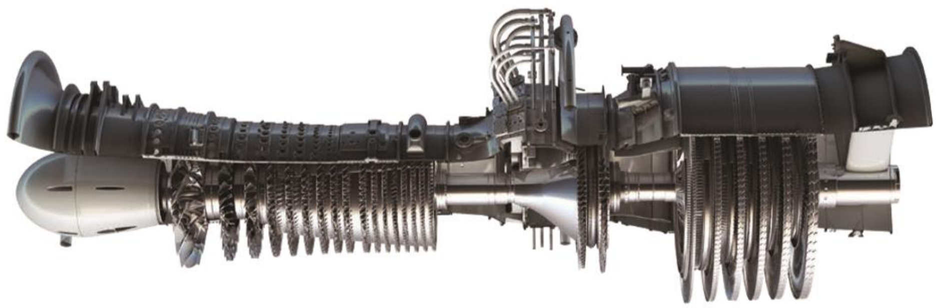


Figure 14: Cut through model of the GE LM 2500 Gas turbine [41]

Relevant data for the LM 2500+ turbine as stated by GE in their product sheet [42]:

Table 4: Relevant data for the LM 2500+ turbine stated by GE

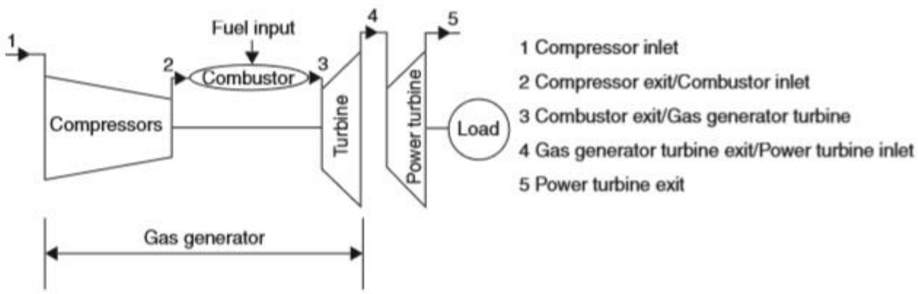
"Gross Heat Rate (Btu/kWh, LHV)	9.169"
"Gross Heat Rate (kJ/kWh, LHV)	**9.674"**
"Gross Efficiency (%, LHV)"	**37.2%**
"Exhaust Temperature (°C)	539"
"Exhaust Energy (MM Btu/hr)"	175"
"GT Turndown Minimum Load (%)	50%"
"NOx (ppm) (@15% O2)	25"
"CO (ppm) (@15% O2)	25/25"
"Startup Time (Hot, Minutes)	10"

For comparison relevant data for the LM 2500+ turbine stated by independent source:

Table 5: Relevant data for the LM 2500+ by independent source [43]

«Fuel consumption	(215 g/kW-hr)»
«Heat rate	6.522 Btu/shp-hr»
«Heat rate	**(9,227 kJ/kW-hr)»**
«Exhaust gas temperature	965ºF (518ºC)»
«Turbine speed (rpm)	3,600»
«Thermal efficiency	**38%»**
«Weight	5.25 ton2

Working principle of the LM 2500 + turbine is shown below:



11.39 Schematic representation of a two-shaft gas turbine operating with a free power turbine.

Figure 15: From Jahnson Peter. Modern Gas Turbine systems p 486. [44]

3.6.7 The General Electric LM 2500 PE Gas turbine.

The LM 2500 PE gas turbine is an upgraded LM 2500 turbine. According to GE`s fact sheet, the letters PE indicates “GE offers two steam injection systems for increased power on the LM2500-PE* gas turbine: the LM2500-PE with Steam, which allows up to 30,000 pph of steam” [45]. In principle, a steam injection system for a gas turbine looks like the one described in Figure 16:

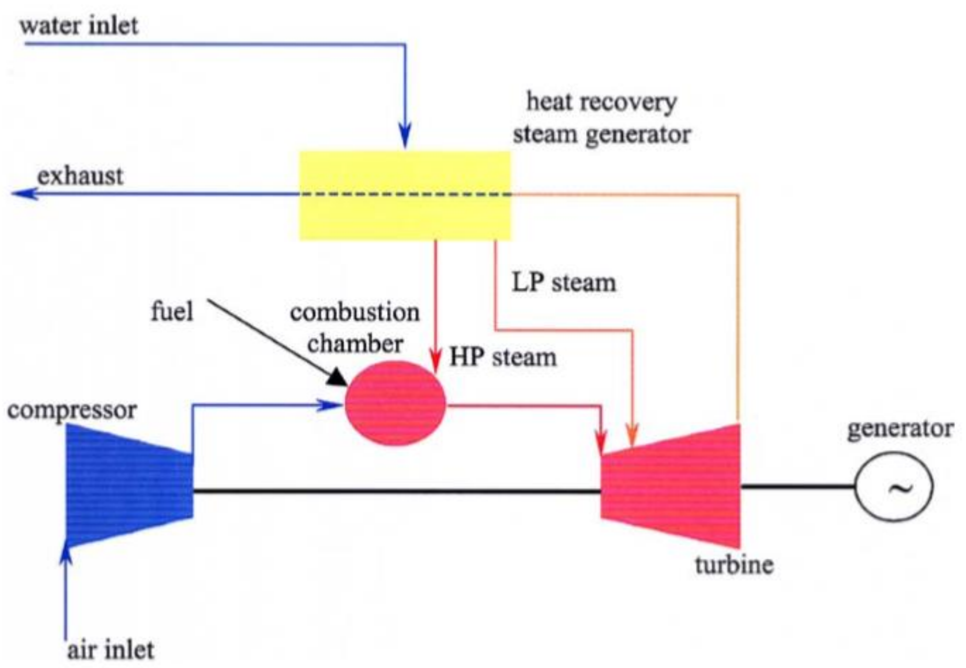


Figure 16: Principle drawing of a steam injection system for a gas turbine [29]

3.6.8 Waste Heat Recovery from Gas turbines

As seen above, the exhaust gas still has a temperature of around 500 °C when exiting the gas turbine [46]. A substantial part of the heat energy from the combustion process remains in the exhaust gas. According to GE`s own figures the exhaust gas of the GE LM 2500+ turbine still contains 175 MM Btu/hr of energy. [42]

To avoid that this energy goes to waste it is common to install some kind of exhaust gas boiler or waste heat recovery unit (WHRU) to recover the energy, and thus increase the overall efficiency of the plant.

Gas turbines in simple cycle set ups can at best achieve around 40% thermal efficiency. While complex cycle with "intercooling, reheat and regenerating can achieve thermal efficiencies of nearly 60%." [44] This being said, 60% is unrealistic in an offshore environment. To gain efficiency more add on equipment and more space is needed, and space is very expensive offshore. The highest thermal efficiency for gas turbine power generation reported offshore in Norway is 45% and the average is approximately 32%. [47]

3.6.9 Limiting factors for the efficiency of gas turbines

By looking at the equation presented in chapter xx from A. Lund's "Termodynamikk & Strømmingslære" it can be seen that in order to obtain higher thermal efficiency of the machine, there are several potential improvements to be made [35]:

$$\eta_t = 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{3.17}$$

- A high as possible turbine inlet temperature is desirable T_4.
- As low as possible compressor outlet temperature T_2(but as high as possible pressure ratio)
- To take as much as possible energy out of the process before heat is rejected to the heat sink (as low as possible T_4)

The gas turbines has historically been perceived as inefficient [48].

3.6.10 Developments to increase inlet temperature, in order to enhance thermal efficiency

With regards to challenge number one, to increase the turbine inlet temperature there have been done several improvements from around world war 2 and until present day.

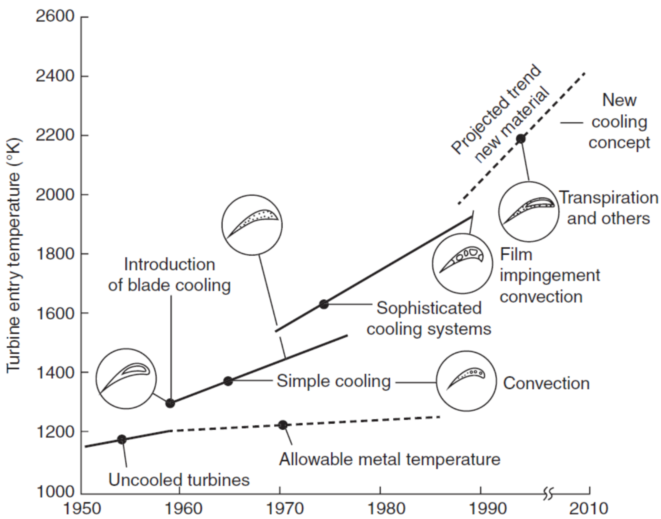


Figure 17: Turbine inlet temperature inlet temperature improvement from 1950 – today [28].

The gas turbines has historically been perceived as inefficient. "it efficiencies were as low as 15%" [48]

3.6.11 Cycle alterations to enhance thermal efficiency; recuperation, intercooling

As the formula for thermal efficiency is showing, it is beneficial to lower compressor outlet temperature T_2, but to increase combustion chamber inlet temperature. To obtain this, the two concepts intercooling and recuperation have been introduced:

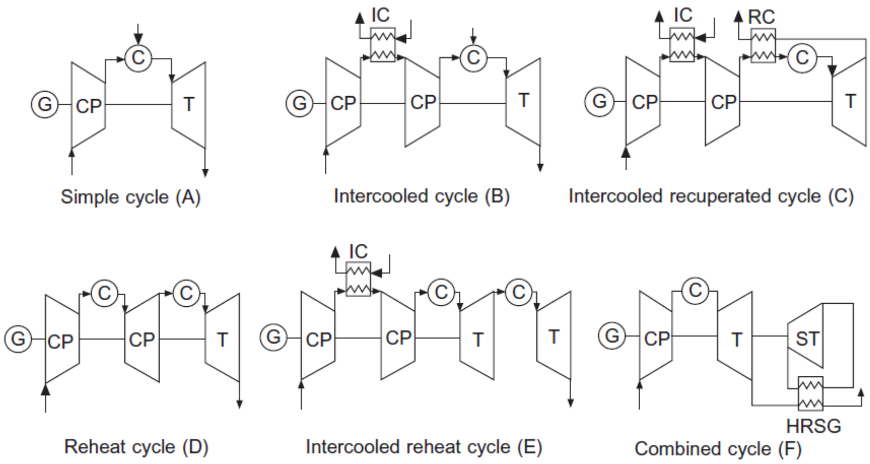


Figure 18: Various arrangements for improving the thermal efficiency of gas turbines, from pounders Marine Diesel Engines and Gas Turbines [49]

For the last improvement point, to take as much energy as possible out of the process before heat is rejected to the heat sink, exhaust gas boilers, economizers or other waste heat recovery unit are in use. Either in order to produce steam for use elsewhere in the process, or for large scale plants in a separate Rankine cycle generator, or to produce steam to inject into the turbine, either in a STIG or Cheng cycle, ref the earlier described LM 2500 PE turbine, which has this option.

As a result of the above described improvements, the gas turbines are now reaching efficiencies over 40% [49] in simple cycle arrangements, over 60% in Combined cycle arrangement [50]. On the figures below it is shown that the intercooled, recuperated gas turbines are getting close to the modern large 2-stroke, low-speed, long-stroke diesel engines which are the most effective heat engines built to date. 2 Stroke low speed diesel engines have other challenges such much higher space requirements and more frequent maintenance, which increases OPEX cost.

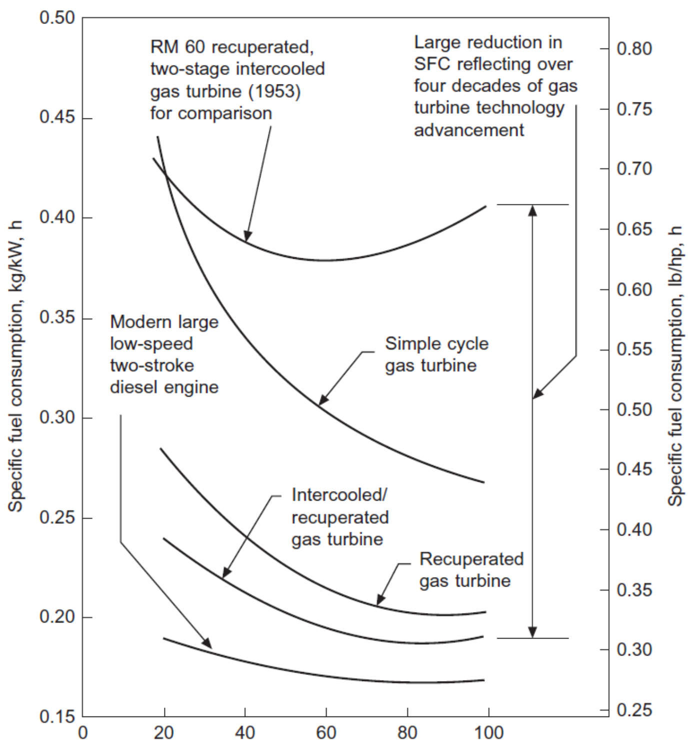


Figure 19: Comparison of SFC against load for various gas turbines [49]

3.6.11.1 Part Load operation of gas turbines.

From the chart above, one can see that the early gas turbines had very bad part load efficiency curves. Maximum efficiency was only reached close to 100% load. Compared to the relatively flat and much lower curve for the 2-stroke low-speed diesel engine, one can understand why nearly all oceangoing cargo vessels of large size that is competing in the very competitive globalized shipping industry, has chosen the 2-stroke low speed diesel engine, that in addition burns residual fuel oil at approximately half the price of marine gas oil.

However, when studying the curves for the modern gas turbines it is apparent that they are closing in on the 2-stroke diesel engine, at also has relatively flat SFC curves all the way from approximately 60% until full load at 100%.

The most important disadvantage of the gas turbine as a prime mover for ship propulsion and in our case generators in a relatively small power grids, like the grid onboard an oil production platform, is the relatively poor part load thermal efficiency at part load. “For example, at 50% load, the gas turbine achieves around 75% of the full-load efficiency, and at 30% load this drops to 50% of the nominal efficiency” [51]

To prevent this drastic drop in thermal efficiency gas turbine manufacturers of modern gas turbines has built in various mechanisms to prevent the reduction in performance, “such as the controlled inlet guide vanes and multi-shaft designs, are employed to improve the part-load performance. Other modifications of the cycle include reheat, inter-cooling and recuperation" [51]

But when the load of the gas turbine drops below 50%, it is in fact not very efficient. Gas turbine manufacturers like GE Power are using a term called: GT Turndown minimum load. For the LM2500+ the GT Turbine minimum load is 50%. Below this point the manufacturer can not guarantee that efficiency and NOx and C02 emissions are according to stated specs.

3.6.12 Fuel for gas turbines

The most common fuels for gas turbines operation are kerosene, diesel and natural gas. Kerosene is a finely refined fraction of hydrocarbons with the advantage of high calorific value, and low amount of corrosive substances such as Sulphur. The disadvantage is price. Diesel is a heavier part of the distilled crude oil. A little bit cheaper but contains more corrosive substances. The exact content and specifications of natural gas depends to a large degree on which oilfield it comes from, but in general it mostly contains more than 80% Methane, and it is an excellent fuel for gas turbines with little amount of corrosive substances. Calorific (lower heating value (LHV)) and spot prices for comparison are listed below in Table 6: . Calorific (lower heating value (LHV)) and spot pricesTable 6 [52]:

Table 6: . Calorific (lower heating value (LHV)) and spot prices

Fuel type	Calorific Value (LHV)
Kerosene	43 124 kJ/kg
Diesel	42 600 kJ/kg
Natural gas	38 000 – 50 000 kJ/kg
Sample natural gas	48 120kJ/kg

Aircraft engines almost exclusively use kerosene. Diesel is common for military, marine and offshore use. For land-based power generation plants an offshore production platform power production the use of natural gas is most common.

3.7 Offshore wind energy

3.7.1 Overview

This chapter starts with a brief description of the wind industry today along with recent developments within the industry. Secondly, components and their function are described to give the reader an understanding of challenges and main cost drivers, including operation and maintenance.

Figure 20: Source – Ole Jørgen Bratland/Equinor

At the end of 2017, world wind generating capacity reached 539 000 MW. After four decades of modern development, generating electricity from wind is now accepted as “mainstream” grid power generation. The reason is the development of more reliable and cost effective solutions for wind generation. In 2017 grid-connected offshore wind projects had an average size of 493 MW, increased by a third from 2016. For individual turbines the size installed was 5.9 MW, a 23 % increase from previous year. For the completed and partially completed wind farms, the average install depth was 27.5 m and distance to shore 41 km. The trend is clear; bigger, more powerful and further from shore. A large share of these are supplied from Siemens and Mesta.

Large machines used for power grid network supply range from 3 to 8 MW with rotor diameters between 80-120 m. One such 8 MW turbine can power 5 500 homes annually. Wind power supply to grid networks is predominantly from wind farms, as opposed to single or small grid turbines. At a windfarm, each turbine needs to be cited about 7 or more rotor diameters from its nearest turbine, to not steal wind from one another. For the largest turbines this may mean ½ - 1 km distance between each turbine. Thus, the seabed with the state as the only owner, is a natural place to install larger windfarms. This of course, is not the only reason to place wind turbines offshore. Higher wind speeds and more stable conditions makes it necessary to move offshore if the new high capacity turbines are going to reach their full potential.

3.7.2 Definitions

The GL Guidelines for certification of wind power plants use the definition *"rotor-nacelle assembly including the support structure"* for wind turbine and "*turbines and substation(s) including their support structures, power cables and the control station*" for power plants [54]. In this thesis, wind farms refers to arrays of 4 or more turbines connected as a group to export electricity to a grid network, including their support structures, power cables and the control station. The term wind turbine can refer both to onshore, offshore and floating wind rotor-nacelle assemblies including support structure. Grid networks refers to the infield power collection for offshore fields, transported via cables, either to transformer stations or directly to installation. Offshore substations, transportation cables etc. are referred to as balance of plant(BOP).

3.7.3 Working principles and components

Windmills produce electricity by transforming kinetic energy to electrical power. A windmill basically uses the same principles as an aeroplane wing, a boat sail or helicopter rotor. To understand what these have in common, one must first look at their shape, see Figure 21.

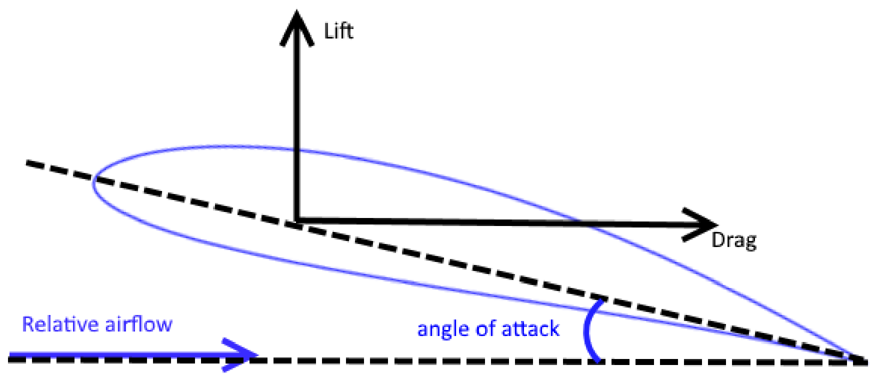


Figure 21: An aerofoil nomenclature. Cross section of an aerofoil with a convex upper surface forcing the airflow to accelerate.

In physics, lift created by a foil shape can be explained by two principles, Bernoulli equation and Newton's 3rd law of motion. A cross section of a foil is shown in Figure 21, the air passing (in a smooth, laminar flow) has a higher velocity over the top of the wing than beneath. According to Bernoulli's equation an increase in velocity means a drop of pressure. Bernoulli's equation is shown below:

$$p + \frac{1}{2}\rho V^2 + \rho g h = constant \qquad (3.18)$$

Where p is the pressure, ρ is the density $[\frac{kg}{m^3}]$, V is the velocity $[\frac{m}{s}]$, h is elevation [m] , and g is gravitational acceleration$[\frac{m}{s^2}]$.

As a result the wing wants to go where there is least pressure, upwards. If considering an airplane wing, this suction-effect is what causes the lift force to act on the wing. The perpendicular drag force, made as small as possible, is overcome by the airplane engine.

The other contributor is Newtons 3rd law of motion which says that for every action, there is an equal and opposite reaction. In short, this means that the air pushed downwards by action of the air foil, is pushed upward as a reaction. These effects produces a torque on the rotating shaft of the turbine. To sustain the lift force, the air has to leave the blade smoothly at the trailing edge to not cause turbulence.

The attack angle is the angle between the relative airflow and the cord line from the front and rear of the blades cross-sectional area. This angle sets the pressure difference between the top and bottom of the blade, and therefore the amount of work that is exercised by the wind. At a given wind speed the rotation speed increases with increasing attack angle, up to a certain value. Turbulence can occur if the attack angle between the relative airflow direction and chord is too steep. To gain optimal lift, the foil has to be tilted to the right angle of attack. This feature is important because right design of the blade profile allows optimum values of angle of attack and blade setting, both of which should remain constant for maximum power extraction, whatever the speed of the unperturbed wind. The optimal angle for maximum lift and minimum drag is dependent on the individual foil shape and whether the flow is laminar or turbulent. This adjustment mechanism, called pitching, is used when the wind speed is between rated and shut-down values. At wind speeds larger than 12 m/s the structural load caused by the wind becomes more significant. At wind speeds over 25 m/s the blades are rotated to the point where no electrical energy is produced to prevent damage.

The nameplate capacity stated by the manufacturer is a hypothetical maximum when running full time. The individual stated capacity of the turbines planned at Tampen is 8 MW. If operated non-stop for an entire year, each turbine would produce (8 MW) x 365 days x 24 hours = 70 080 MWh. Siemens SG 8 – 167 DD offshore wind turbine has a stated annual energy production to grid per turbine is 34 000 MWh. When the average power generated is divided by the rated peak power, the capacity factor is given. For the mentioned turbine, the capacity factor is 48.5 %.

Components

A windmill contains up to 8 000 different components. In the following section the main components and their function are explained to provide an understanding of how the kinetic energy is converted into electrical energy. There are two principles for converting the energy potential in wind, vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). The horizontal axis wind turbine is by far the dominating technology and what most people associate with windmills. This thesis will only involve horizontal axis wind turbines as it focuses on big wind applications.

Wind turbines used for electricity generation requires large speed at small torque. A limiting rotational speed factor for turbine blades is moving in to air strongly perturbed by a previous blade. Thus, fast-turning rotors for electricity generation should have few blades. At the same time, only 1 or 2 blades make the rotor motion very uneven. As a result, three-bladed rotors have become the norm on land and the initial offshore farms that use design developed for onshore sites.

From the rotor hub goes a low-speed shaft into the gearbox which connects it to the high speed shaft. This increases the rotational speed from 30-60 rotations per minute (rpm) to about 1 000 – 1 800 rotations per minute, needless to say, this is a heavy and expensive part of the turbine. As a result, gearless turbines has entered the market and may become the new standard within wind energy. With these turbines the generator rotates with the same speed as the blades.

The generator transforms the mechanical energy into electrical energy. As mentioned above, the large gearing gives the nacelle a considerable larger number of rotations per minute than the rotor. This generates a moving electric field around the stator, which is the stationary part of the rotary system. Alternatively for gearless turbines with less rpm, the generator is designed with more poles to compensate for the reduced rotational speed.

Floating wind turbines is at an early stage of development and the only full-scale wind farm of such kind is Hywind outside Scotland. The principles behind the floating structure is well known from the petroleum industry and the three most common types are the spar-buoy, semi-submersible and the tension-leg-platform (TLP). [55] [56] The spar-buoy is shown to the left in the figure below.

Figure 22: [57]. From the left: spar-buoy, semi-submersible and TLP.

The cost distribution varies with size, foundation, infrastructure among others, but a report published by Douglas-Westwood shows a capital cost structure of an offshore wind system which roughly shows the share of total cost in percent for the different components. This table shows how each of the components contributes to the total capital cost.

Table 7: List of cost components in USD/kW and share of total cost [58].

	Share of total cost (%)	Cost(USD/kW)	Sub-Components	Cost share of sub-components (%)
Wind turbine	44	1970	Nacelle	2
			Blades	20
			Gearbox	15
			Generator	4
			Controller	10
			Rotor hub	5
			Transformer	4
			Tower	25
			Other	15
Foundations	16	712	-	-
Electrical infrastructure	17	762	Small array cable	4
			Large array cable	11
			Substation	50
			Export cable	36
Installation	13	580	Turbine installation	20
			Foundation installation	50
			Electrical installation	30
Planning and development	10	447	-	-
Total	100 %	4 471		

Electrical infrastructure required for a wind park should also be mentioned. The cable cost comes from internal array cables and export cables. Two wind farms with the same rated power can have different costs and output dependent on their layout. For an 8 MW turbine the recommended radius is 1000 meters around each unit. This means that even if the wind park exports the power to the nearest oil & gas installations rather than onshore, significant lengths of cable is required. The array may be setup parallelly or in series, where series is cheaper, but also induces more risk. A major cost saving could be obtained by choosing the right cable. It is therefore important to choose a reasonable trade-off in terms of cost, robustness and ability to prevent electrical losses.

The electrical output current from wind turbines is alternating (AC), usually 33 kV, which can be transported directly to shore without transformer platforms [58].

For smaller projects like this one, up to 100 MW and distances up to 60 km, AC-cables are used as export cables. With larger wind parks and longer distances, the use of AC-cables will lead to too much loss in cables and HVDC may be more cost effective. A cost assessment study has evaluated an offshore wind power project on the Galician Coast [59]. The wind farm has a similar setup as the case study in this thesis, an array of 14 x 8 MW turbines. The graph below is borrowed from the study and shows the most cost effective solution at increasing distances.

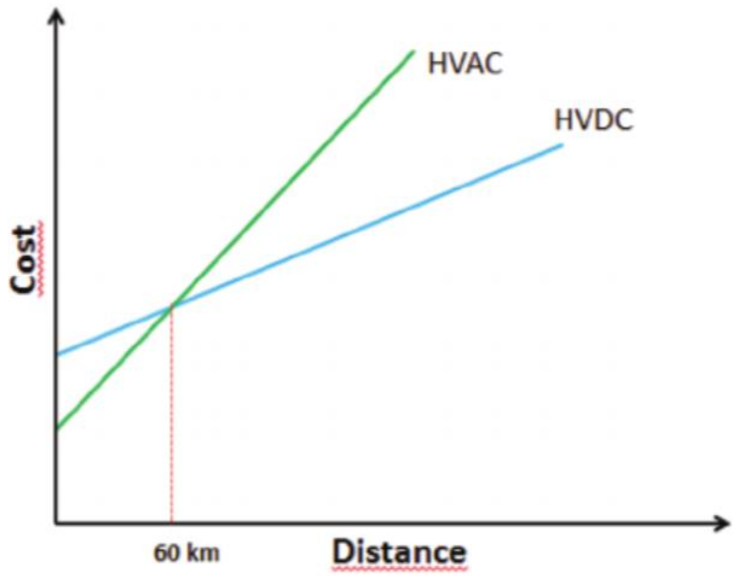


Figure 23: Cost – electrical cable distance graph.

Distances above 60 km HVDC-cables where the electricity is transformed from 33 kV to 132 kV or more, is a better alternative [58]. The distance between Gullfaks C and Snorre A is approximately 27 km, and the wind farm is located between these installations, small distances in other words. Douglas Westwood estimates the capital cost of electrical infrastructure to about 17 % of the capital expenditures, these numbers might be lower for this project as nothing needs to be exported over long distances.

3.7.4 Wind resources

In this section, procedures for how to estimate available wind resources and energy potential in the wind are presented for the reader to understand the basis of the results presented later in the thesis.

Wind energy is the result of the atmosphere being a dynamic systems which is constantly trying to trying to reach equilibrium (Le Chateliers law). Offshore wind resources are good in general with relatively small geographical variations, see Figure 24. However, wind speed vary with time and an average number is not enough to provide a good description of the wind resources. To obtain a better description of the wind speed, a statistical model is used. The distributed wind profile of an area can be described by using a Weibull distribution. The shape of the Weibull distribution is described by a form factor, a higher form factor means a higher frequency of mean wind velocities [60]. This is described more thoroughly in section 3.7.6.

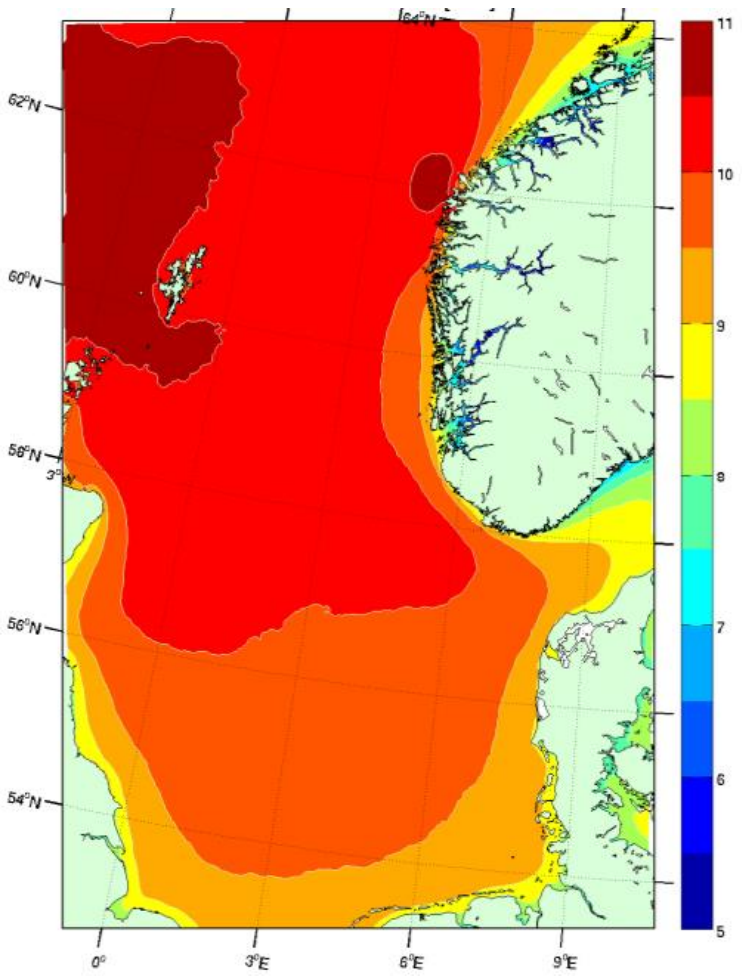


Figure 24: Yearly mean wind. From WRF (Weather Research and Forecasting) simulation. The colour bar to the left shows the average wind speed [m/s]

The wind map above shows that the North Sea area is a well suited location for a wind park.

3.7.5 Extrapolation of wind speeds

The ideal would be to collect measured wind data at hub-height, but with new turbines raging 120 m above sea level the feasibility is both technologically and economically challenging. Instead, wind speeds are measured closer to the ground, usually at around 10 metres, and estimated for the relevant height using a method for extrapolation of vertical wind speed profiles. Of course the longer the extrapolation distance, the bigger the error. In this thesis the wind speeds are extrapolated from approximately 80 to 100 meters, which gives rather small differences and accurate results for this application. Two of the methods, or mathematical models, used for extrapolation are the log law and the power law, both which are subject to uncertainty caused by the variable, complex nature of turbulent flows [61]. As this is an economic assessment it would be beyond the scope of this thesis and of little relevance to derive each mathematical equation presented, thus they will be presented and explained in brief. However, if the need of deeper knowledge should arise, the derivation of the following equations can be found in almost every academic text book covering wind energy.

Log law

The logarithmic wind profile equation is given by

$$U(z) = \frac{u^*}{k} \ln\left(\frac{z}{z_0}\right) + \varphi(z, z_0, L), \qquad z \geq h \tag{3.19}$$

Where u* = friction velocity (or shear velocity) [m/s], k = dimensionless von Kármán constant ≈ 0.4 [-], z_0= is surface roughness [m], which is also known as the roughness length, and U(z) = the wind speed at height z. φ is a stability parameter where L is the Monin-Obukhov length. Under neutral stability conditions in the atmosphere, this parameter falls out. u* is related to the momentum flux (t) at the surface by:

$$u_*^2 = \frac{\tau}{\rho} \tag{3.20}$$

Where τ is the shear stress and ρ the density. This is a measure of the friction force acting on a fluid passing over a surface.

In some literature z = z'- d, where the zero plane offset (*d)* is the height above the ground where there is zero wind speed due to obstacles as tress and buildings. This is usually set to 2/3 of the mean height of the obstacles. Offshore there are few obstacles above sea level, thus z is set equal to hub height.

Roughness parameter and Monin-Obukhov length

The uneven surface of the earth creates a friction between the surface and the atmosphere. At the same time objects at the surface creates turbulence. As a result, parts of the kinetic wind energy are transformed into mechanical energy. This is the main reason for wind speeds being lower at the ground than further up the atmosphere. Turbulence is created at the ground and propagates through the air layers. As we elevate, the mechanical turbulence and the friction forces is gradually being reduced. The terrain can be described by the roughness parameter, z_0. This is an important factor and is defined in the DNV-standard as:

$$z_0 = \frac{A_c}{g}\left(\frac{k\bar{v}}{ln\left(\frac{z}{z_0}\right)}\right) \tag{3.21}$$

Where g is the acceleration of gravity and A_C is Charnock's constant. Charnock's constant describes the wave behaviour, whether it is partially or fully developed, velocity and water fetch.

The resource predictions are not affected significantly by the varying roughness of the sea if the lowest height from which the extrapolation to hub-height is above 10 m [62]. From DNV's table below, the estimated roughness parameter for open sea with waves is set between 0,0001-0,01. 0,0001 m in open sea without waves and 0,001 in coastal areas with onshore wind.

The average change of wind speed with height presented in Equation (3.5), only has a logarithmic profile under near-neutral atmospheric stability. The stability indicates whether turbulence or waves will develop in the atmosphere with growing altitude (unstable), or if the atmospheric flow is laminar (stable).

Table 8: Typical values for z_0 for various types of terrain. [63]

Table 2-1 Terrain roughness parameter z_0 and power-law exponent α		
Terrain type	Roughness parameter z_0 (m)	Power-law exponent α
Plane ice	0.00001-0.0001	
Open sea without waves	0.0001	
Open sea with waves	0.0001-0.01	0.12
Coastal areas with onshore wind	0.001-0.01	
Snow surface	0.001-0.006	
Open country without significant buildings and vegetation	0.01	
Mown grass	0.01	
Fallow field	0.02-0.03	
Long grass, rocky ground	0.05	
Cultivated land with scattered buildings	0.05	0.16
Pasture land	0.2	
Forests and suburbs	0.3	0.30
City centres	1-10	0.40

Monin-Obukhov is a measure of the height above the ground where the turbulent dissipation due to buoyancy is comparable with the shear stress production of turbulence [64]. It is defined as the length, represented by the air layers next to the ground, dominated by mechanical turbulence. The measure form express the influence from heat flux and the friction velocity (u*) on turbulence formation. The length L is the height at which the vertical shear production of turbulence is in equilibrium with stable air conditions that counter the turbulence. For unstable conditions there are no such equilibrium and L has a negative value. For stable conditions the value of L is positive, and for neutral conditions it rises to infinite values. The Monin-Obukhov length can be expressed by the following equation:

$$L = -\frac{\overline{\theta_v} u_*^3}{kg\overline{(w'\theta')}_s} \tag{3.22}$$

Where $\overline{\theta_v}$ is the mean virtual potential temperature [K], g the gravitational acceleration [m/s^2] and $\overline{(w'\theta')}_s$ the surface virtual potential heat flux [mK/s].

Power law

The alternative power law can be expressed as

$$U(z) = U(H)\left(\frac{z}{H}\right)^a \tag{3.23}$$

Where the power law exponent *a* depends on the terrain roughness [63]. U(z) = wind speed at height z, (U)(H) = wind speed at reference height [m/s], z = height [m], H = reference height [m].

3.7.6 Weibull distribution of wind speeds

In most places the wind speed frequency distribution through a period can be described by a Weibull distribution. The Weibull distribution is a function of mean wind speed and the parameters λ and k.

$$f(\bar{u}; \lambda, k) = \left(\frac{k}{\lambda}\right)\left(\frac{\bar{u}}{\lambda}\right)^{k-1} e^{-\left(\frac{\bar{u}}{\lambda}\right)^{k}} \tag{3.24}$$

λ is called the scale factor and describes the skewness of the probability distribution, how much it shifts to the right. When the value of the scale factor increases, it is illustrated by a less sharp top which indicates a larger average wind speed.
k is called the form factor and shows the sectioning of the function. When this value increases, the top of the curve turns sharper which indicates less wind speed variations. k=2 are used by most Norwegian weather stations. This is really a special case of the Weibull distribution, called the Rayleigh distribution. *u* is the wind speed [m/s] and *f* shows the probability for that wind speed.

The mean wind speed is given by:

$$\bar{u} = \int_0^\infty u p(u) du \tag{3.25}$$

This will be calculated as the average of the measured data.

3.7.7 Calculating wind energy

The wind power per unit area can be determined by starting off with the continuity equation of fluid mechanics:

$$\frac{dm}{dt} = \rho AU \tag{3.26}$$

which is a function of the velocity, U, density, ρ, and swept area, A. This function describes the mass flow rate through the swept area of a turbine, see Figure 25.

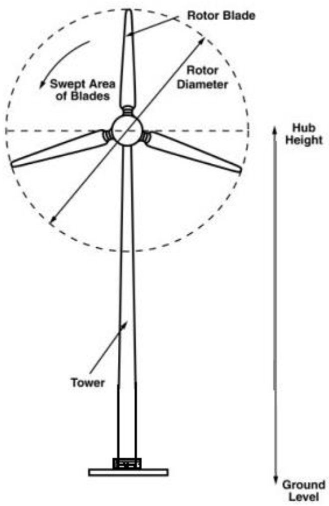


Figure 25: Swept area of a wind turbine.

The power of the flow (kinetic energy per unit time) is given by:

$$P = \frac{1}{2}\frac{dm}{dt}V^2 = \frac{1}{2}\rho AV^3 \tag{3.27}$$

And per unit area, P/A, the function becomes:

$$\frac{P}{A} = \frac{1}{2}\rho V^3 \tag{3.28}$$

Where P = Power, A = Area, $\rho = density$ and V = wind speed. This formula is only valid for wind entering from a perpendicular direction.

Note from equation 3.3 and 3.4 that the wind power density is proportional to the cube of the wind velocity [65]. Hence, a location with steady, high wind velocity conditions is the number one most important factor when planning a new wind power plant.

The wind turbine will not be able to benefit from all the energy in the air stream, as 100 % absorption would eliminate the airstream and stop the turbine. Betz's law indicates a theoretical limit for the maximum power that can be extracted from the wind. According to this law, no turbine, independent of design, can capture more than $\frac{16}{27}$ of the kinetic energy in the wind. This number is known as Betz's coefficient.

3.8 Cost considerations

As stated earlier, floating wind technology is at an early stage of development and realized projects consists of mainly prototypes and pre-commercial arrays. Lack of data makes it hard to establish a proper cost structure for floating offshore wind farms. While there are fairly robust information available on costs for fixed-bottom structures, data on floating turbines carry greater uncertainty. These early prototypes, which is the primary source of information do not reflect the true costs that can be expected with mass deployment [66]. It must be emphasised that there is a distinguish between basic costs and final prices. *Basic costs* undertaken by the project owners like capital expenditures and operation and maintenance are not the same as the *price of wind* which reflects the price an owner expects to receive per kWh in a power purchasing contract. This thesis considers wind energy as an alternative to gas turbines, not as an alternative to buying electricity from the grid or other grid suppliers. Hence, the basic costs are the main concern for this thesis.

The reader should note that that cost estimates outlined in this section are based on existing data, publicly available. To try to make estimations based on exact steel weight, local bottom conditions and so on with the lack of reliable information would carry too much uncertainty. Interviews confirm that even for those working close on large scale, floating, wind farm projects there are too many uncertain factors to accurately estimate CAPEX and OPEX costs, and how they will develop in the future. Since the information found on wind farm costs are quite widespread and in many cases subjective, a choice has been made to collect cost data mainly from two sources, with support from other sources where information is not available. Both has been referred to earlier in the text. The first source is a report issued by the Carbon Trust on behalf of the Scottish Government. This is a thorough report based on several studies on both floating and fixed-bottom structures. The report considers costs for several sub-structures at both prototype, pre-commercial and commercial level. The other source of information is the study on wind farm at the Galician coast. This wind farm has a total capacity of 112 MW consisting of 8 MW turbines form Vestas. The wind farm also has a short distance to shore (20 km), making costs for electrical infrastructure comparable to the short distance between the wind park and O&G installations at Tampen [59]. Because the Galician coast, unlike the north sea, lacks a large continental shelf, a floating support platform rather than the monopile is considered in that study. This is a more expensive solution than the monopile.

It is important to point out where in the value chain costs are considered. When discussing energy costs there is a significant difference in analysing costs at the electricity outlet or location of the turbine. These differences are most significant for long distances and onshore grid supply, where it is not necessarily the owners who pays for grid connection and reinforcement [67]. As power supply for oil and gas installations it is assumed that these costs are covered by the project owners, in this case the operators who see this as an alternative for gas turbines.

There are several input factors needed to calculate the cost of energy, see Figure 26, where the most important are capital expenditures (CAPEX) and operational expenditures (OPEX), lifetime of project, output from wind turbine dependent on capacity and available wind resources, and the cost of capital.

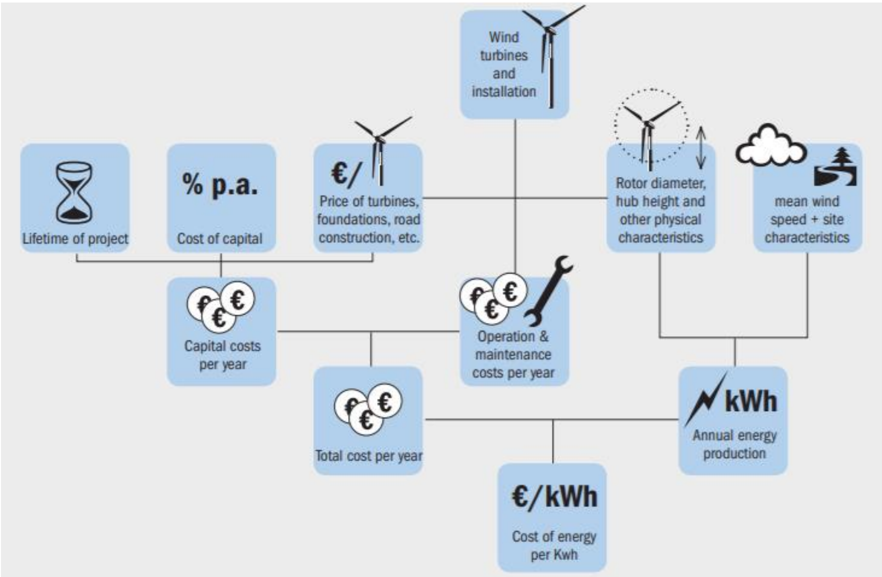


Figure 26: The cost of wind energy [67]

3.8.1 Challenges facing the wind industry

Several challenges can be mentioned in all stages of the project and throughout the lifetime of a wind park. The reason those challenges are listed here is that they affect the cost level in the wind industry a great deal. When solved, this will make wind a more effective source of energy. Due to growing investments in the wind industry several new methods and solutions to for these challenges are expected in the future. With technologies at the infant stage, like floating wind, commercially sensitive information about new experiences or lessons learned, are of kept close to the heart by developers. This problem can be solved by introducing industry guidelines and standards. DNV GL-ST-0119 is one such standard that has newly been revised by DNV, they have also released a new guideline for certification of floating wind turbines, DNV GL-SE-0422 [68]. As the technology matures and new solutions enter the market, the costs are expected to decrease and more accurate estimations can be made.

In order to develop proper simulation tools for the design phase, results need to be compared to real world data for validation. At this point, there are limited data from full-scale testing of floating turbines [69]. There is also a demand for adapted testing facilities generating both wind and waves. SINTEF are currently developing and testing such facilities [70].

Mooring and anchoring systems used today are often borrowed from other industries, like oil and gas. These are very expensive and may not be adapt very well to floating turbines. The reason is that a typical oil- and gas installation is positioned at larger depths. Equinor’s Hywind is placed at 100 metres depth outside Scotland, the Visund field, as an example, have a water depth of about 300 metres. Shallower water may lead to more stress on the anchor connectors and it may be necessary to develop new anchor systems.

When developing wind farms for oil and gas purposes, there is no standard for distribution of electrical energy. One solution is to use transformer platforms for collecting energy before distributing it to the oil and gas installations. This requires robust electrical cables flexible enough to account for the movements arising. Another solution is to connect the windmills directly to the platforms individual breaker panel.

The wake effect is a known phenomenon within the wind industry [71]. Windmills affect each other by "stealing" wind if standing too close. Software like WASP can help wind park owners decide an optimal position relative to each other. However, floating turbines will not only affect each other by stealing wind resources from each other, they will also affect their movements in the water. This again leads to new wake effects which must be accounted for in the planning phase.

3.8.2 Planning Costs

Planning costs include all costs related to the project prior to capital expenditures. This includes feasibility studies, site selection, planning size, layout and distribution, and licenses for the project.

Table 9: The table lists planning costs from different reports and projects [59].

Planning costs for offshore wind farms		
Reports	Planning costs [MNOK/MW]	Capacity [MW]
Douglas-Westwood	3.4	600
UK ERC	4.8	90-504
Crown State	1.5	500
Scottish Enterprise	2.5	500
R. Howard	2.2	500

WindFloat from Principle Power was a 2 MW prototype installed in 2011. It was the first of its kind with a semi-submersible platform, the planning costs shown is therefore not representable for a commercial project like the Tampen wind park where a single prototype has already been tested outside Scotland. The other numbers shown are evaluations of wind farms with bottom-fixed structures. Less restrictions on choice of location may lead to lower planning costs for wind farms with floating structures compared to bottom-fixed structures, in the future. For reasons mentioned earlier, planning costs for floating wind will be at the upper level or above costs for bottom-fixed projects until the industry is more standardised. In this analysis, planning costs will be set to 5 million NOK per MW.

3.8.3 Capital Expenditures (CAPEX)

The CAPEX include total costs of turbine, balance of plant and installation, this includes support structure, cable and transformer platform. The costs of an offshore wind park can be divided into two categories. The first category contains the production unit, consisting of turbine, tower and foundation. The other category covers infrastructure, consisting of cable network and transformer stations. Two independent reports estimate the first category, production unit, to account for 80 % of the capital expenditures, while 20 % of the costs go to infrastructure [72].

Several reports on cost estimations have been released from private energy consultancy firms and governmental organisations, on both fixed-bottom and floating structures. Among these DNV (2011), GL Harrad Hassan (2012), The European Wind Energy Association (2012) and Blue H Group (2013). These estimates range between 22 to 35 Mkr/MW, see chart below. None of these come close to Equinor's own estimates for capital expenditures. A total capital cost of 5 billion for an 88 MW wind park equals nearly 57 MNOK/MW which ranges well above most wind park estimations published by consultancy firms on a commercial level.

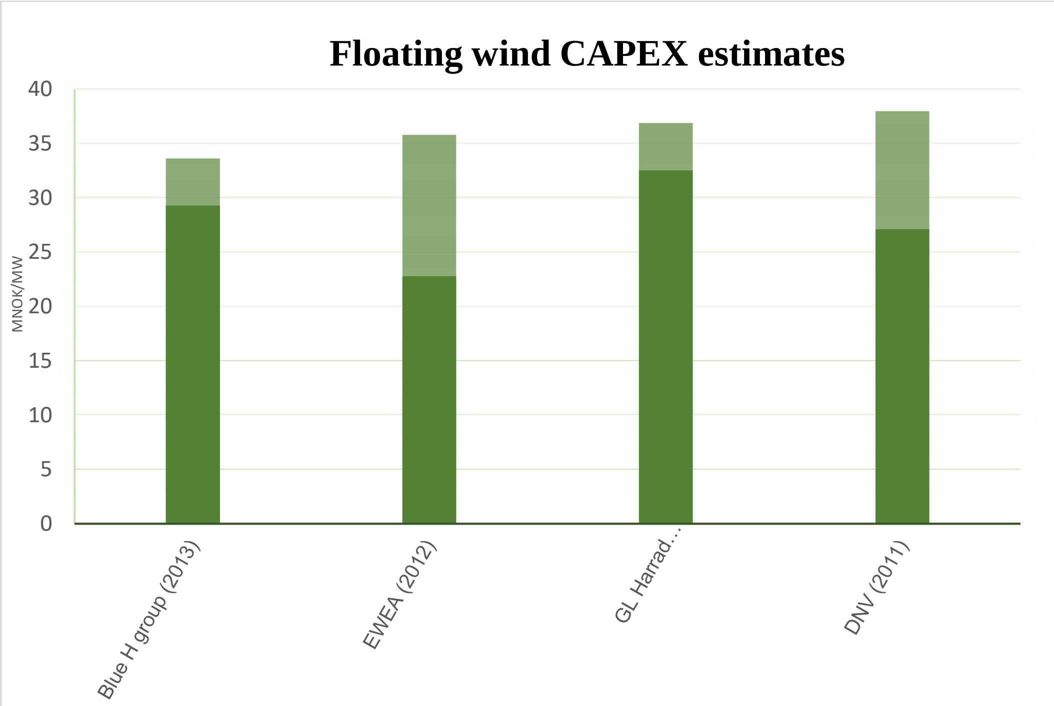


Figure 27: Capex estimates from different consultancy firms. The dark colour shows the lower value in each report and the light colour the range of estimates. The results are gathered from the Carbon Trust report (2015) [73] and converted to NOK using currency exchange rate per October 2018.

When comparing with CAPEX levels for single prototypes, 57 MNOK/MW is closer to those. The planned wind park at the Tampen area with 11 turbines is not a prototype level project, but compared to 600 MW wind parks it does not draw the same advantages in terms of economies of scale. At the same time it is the first project trying to connect to an oil field and supply installations with electrical energy. Unknown integration challenges may arise and lead to extra costs. The costs of developing a small scale, yet commercial wind park with much of technology still at the infant stage, may be most comparable to prototype or pre-commercial arrays.

Below is a table with CAPEX-estimates for floating wind farm projects on prototype, pre-commercial, and commercial level.

Table 10: Table with CAPEX costs for floating wind farms at different stages of development.

Project Costs - CAPEX							
Cost components	%	**Commercial**				**Tampen**	
Platform	0.22	0.594	m£/MW	6.01	MNOK/MW	0.53	MrdNOK
Moorings	0.06	0.162	m£/MW	1.64	MNOK/MW	0.14	MrdNOK
Anchors	0.02	0.054	m£/MW	0.55	MNOK/MW	0.05	MrdNOK
Installation	0.13	0.351	m£/MW	3.55	MNOK/MW	0.31	MrdNOK
Turbine	0.41	1.107	m£/MW	11.19	MNOK/MW	0.98	MrdNOK
Balance of system	0.13	0.351	m£/MW	3.55	MNOK/MW	0.31	MrdNOK
Decommisioning	0.03	0.081	m£/MW	0.82	MNOK/MW	0.07	MrdNOK
SUM CAPEX	1	2.700	m£/MW	27.30	MNOK/MW	2.40	MrdNOK
Cost components		**Pre-commercial**				**Tampen**	
Platform		0.924	m£/MW	9.34	MNOK/MW	0.82	MrdNOK
Moorings		0.252	m£/MW	2.55	MNOK/MW	0.22	MrdNOK
Anchors		0.084	m£/MW	0.85	MNOK/MW	0.07	MrdNOK
Installation		0.546	m£/MW	5.52	MNOK/MW	0.49	MrdNOK
Turbine		1.722	m£/MW	17.41	MNOK/MW	1.53	MrdNOK
Balance of system		0.546	m£/MW	5.52	MNOK/MW	0.49	MrdNOK
Decommisioning		0.126	m£/MW	1.27	MNOK/MW	0.11	MrdNOK
SUM CAPEX		4.200	m£/MW	42.46	MNOK/MW	3.74	MrdNOK
Cost components		**Prototype**				**Tampen**	
Platform		1.144	m£/MW	11.57	MNOK/MW	1.02	MrdNOK
Moorings		0.312	m£/MW	3.15	MNOK/MW	0.28	MrdNOK
Anchors		0.104	m£/MW	1.05	MNOK/MW	0.09	MrdNOK
Installation		0.676	m£/MW	6.83	MNOK/MW	0.60	MrdNOK
Turbine		2.132	m£/MW	21.55	MNOK/MW	1.90	MrdNOK
Balance of system		0.676	m£/MW	6.83	MNOK/MW	0.60	MrdNOK
Decommisioning		0.156	m£/MW	1.58	MNOK/MW	0.14	MrdNOK
SUM CAPEX		5.200	m£/MW	52.57	MNOK/MW	4.63	MrdNOK
Cost components		**Spar**				**Tampen**	
Platform		0.51	m£/MW	5.16	MNOK/MW	0.45	MrdNOK
Moorings		0.17	m£/MW	1.72	MNOK/MW	0.15	MrdNOK
Anchors		0.05	m£/MW	0.51	MNOK/MW	0.04	MrdNOK
Installation		0.42	m£/MW	4.25	MNOK/MW	0.37	MrdNOK
Turbine		2.13	m£/MW	21.55	MNOK/MW	1.90	MrdNOK
Balance of system		0.68	m£/MW	6.83	MNOK/MW	0.60	MrdNOK
Decomissioning		0.16	m£/MW	1.58	MNOK/MW	0.14	MrdNOK
SUM CAPEX		4.11	m£/MW	41.59	MNOK/MW	3.66	MrdNOK

The table above shows estimates for floating concepts in general. This includes devices with multi-turbine platforms or hybrid wind-wave devices. These are heavier and more expensive platforms than TLP, spar and semi-submersible platforms. Thus, the costs above are not fully representable for those. The table below shows cost estimates for the Spar concept alone.

Table 11: Cost estimates for turbines with spar platforms.

		Spar				**Tampen**	
Platform		0.51	m£/MW	5.16	MNOK/MW	0.45	MrdNOK
Moorings		0.17	m£/MW	1.72	MNOK/MW	0.15	MrdNOK
Anchors		0.05	m£/MW	0.51	MNOK/MW	0.04	MrdNOK
Installation		0.42	m£/MW	4.25	MNOK/MW	0.37	MrdNOK
Turbine		2.13	m£/MW	21.55	MNOK/MW	1.90	MrdNOK
Balance of system		0.68	m£/MW	6.83	MNOK/MW	0.60	MrdNOK
Decomissioning		0.16	m£/MW	1.58	MNOK/MW	0.14	MrdNOK
SUM CAPEX		4.11	m£/MW	41.59	MNOK/MW	3.66	MrdNOK

These numbers may better represent the actual costs for this project.

3.8.4 Operational expenditures (OPEX)

More and larger offshore wind parks further from shore necessitates new methods for maintenance, additional to regular workboat-based approach, helicopter and offshore-based working will be needed [74]. As the trend is larger, floating turbines, this fraction is expected to rise in the future. However, as the technology evolves the overall cost/kWh is expected to fall.

The table below lists operation and maintenance costs evaluated for several different wind farms by different consultancy institutions. Table 7 lists operation and maintenance costs for offshore wind parks in general and table 8 lists costs for floating concepts specifically. The O&M costs for floating units are higher than the average, but they are expected to fall in the future.

Table 12: The table lists operation and maintenance costs from different reports and projects [59].

O&M costs for offshore wind farms		
Reports	O&M costs [MNOK/MW]	Capacity [MW]
Douglas-Westwood [32]	0.91	600
UK ERC [33]	0.91	90-504
Roland Berger [37]	1.21	-
OFWT [38]	1.31	500
MOWR[39]	0.51	-

Table 13: O&M costs for projects at prototype, pre-commercial and commercial level

Carbon Trust				
Prototype	0,2	m£/MW/year	2,022	MNOK/MW/year
Pre-commercial	0,14	m£/MW/year	1,4154	MNOK/MW/year
Commercial	0,09	m£/MW/year	0,9099	MNOK/MW/year

Based on the numbers, yearly OPEX costs used in the calculations are set to 85.41 MNOK for the Tampen wind farm.

3.8.5 CAPEX and OPEX estimates used in this thesis

In this thesis, CAPEX estimates are calculated from independent sources, but Equinor have made their own estimate for CAPEX and this will be used for some calculations as well. The reason why Equinor's estimates alone is not used is that there is little information on what these are based on, and they also have ambitions to achieve a 50 % reduction in capital expenditures from Hywind Scotland by 2023, their most recent project. That means that their CAPEX estimate may be reduced before commissioning. This carries to much uncertainty to be used alone.

What is referred to as CAPEX costs for this thesis is the CAPEX presented in Table 11 + an average of planning costs in Table 9. The sum of these two are 3.9 billion NOK and will be used as CAPEX estimate. Some of the results will also be presented with Equinor's own CAPEX estimate of 5 billion.

Since no clear estimate from Equinor has been announced for OPEX costs, all calculations will use OPEX costs equal to 85,4 NOK/year.

4 Model development

4.1 LCOE of Gullfaks and Snorre Powerplants

As mentioned in chapter 2.3 when evaluating the question to install an offshore wind farm at the Tampen area from a commercial point of view, one of the methods used is levelized cost of energy (LCOE):

$$LCOE = \frac{Sum\ of\ cost\ over\ lifetime}{Sum\ of\ El.Energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

[12](2.1)

Where:
I_t: $Investment\ expenditures\ in\ year\ t.$
M_t: $Operattion\ and\ maintenace\ expenditures\ in\ year\ t.$
F_t: $Fuel\ expenditures\ in\ the\ year\ t.$
r: $discount\ rate$
n: $the\ expected\ lifetime$
E_t: $Electricty\ generation\ in\ year\ t$

To make an informed advice to the decision makers fuel expenditures F_t, and investment expenditures $I_t\ needs\ to\ be\ quantified$. The question of approving the Hywind Tampen project or not, is basically an investment decision with two alternatives:

- Alternative 1: Carry out the Tampen Hywind project.
- Alternative 2: Continue with the current arrangements with gas or diesel fired gas turbines.

The discount rate r, and the expected lifetime n, is the same for both of the alternatives. The fuel expenditures, F and the Investment expenditures will vary widely, and will be the decisive inputs to the NPV calculation we will carry out to determine the LCOE of alternative 1 and alternative 2.

4.1.1 Opportunity costs and sunk costs in the case of Hywind Tampen

If the gas produced on Gullfaks and Snorre is not used for production of electricity to run the platform system, or re-injected into the reservoir, the gas can be sold on the energy market. Opportunity cost" is the cost associated with opportunities forgone by not putting the firms resources to their highest-value use." [75] Or simpler explained, the money lost by choosing the second best alternative. At this point one cannot pinpoint if the second best alternative is to sell the gas, and partly use wind for power. Or if the second-best alternative is to continue as before to use gas for electricity generation directly on the platform. This is what this thesis will seek to determine.

When carrying out this analysis it is important to be aware of what is sunk costs and not. For instance, when wind turbines are considered for power generation in 2018, installation costs associated with the gas turbines cannot be taken into account. The platforms are built in 1986-1992, thus these costs are sunk and cannot be recovered. The operation and maintenance expenditures for the existing gas turbine generators on the Gullfaks and Snorre platforms are also to a large degree sunk costs. The platform crew still needs to be onboard, the spare parts for the gas turbines are already bought, and the wind does not always blow, so the gas turbine needs to be ready for start at short notice. On one hand the operation and maintenance costs of the gas turbines are reduced by commissioning the Hywind Tampen project, because the gas turbines will have less running hours, and maintenance intervals are to some extent based on running hours. On the other hand, part of this reduction in maintenance cost will be cancelled by “cycling costs”. Cycling costs are explained in a later chapter.

From a commercial point of view the question really becomes if the reduced fuel costs F and the reduced NOX and CO2 taxes, are large enough to justify the CAPEX expenditure of building Hywind Tampen and to also cover the increased operation and maintenance costs that comes with the wind turbines.

4.2 LCOE for Hywind Tampen

The levelized cost of energy has been calculated with estimates for planning costs, OPEX and CAPEX described in chapter 3. For these calculations, the results presented include NO_x-fund support, and Enova support for 2.5 billion NOK. However, results with Enova-subsidies will not be emphasized. The reason for this is that 2.5 billion NOK is 200 million NOK more than what Enova gave in total support throughout all of 2017 and at present time there are no indications towards a support of that size, publicly at least.

LCOE is also calculated using Equinor’s own CAPEX estimates. The calculations are performed with 7 % discount rate, but a sensitivity analysis is performed with discount rates from 5-10%. In a strictly business-economic sense, a 10 % discount rate is usually demanded. Results are shown for both in Table 14 and Table 15 below:

Table 14: Levelized cost of energy results for Tampen wind park, r = 10%.

	Unsubsidised	Subsidised (NOx-fund)	Subsidised (NOx and Enova)	Equinor (Subsidy from NOx-fund)
Total lifetime costs(NOK)	4,641,729,347.54	4,075,729,347.54	1,575,729,347.54	5,161,137,347.54
Total lifetime output(MWh)	2,796,438.96	2,796,438.96	2,796,438.96	2,796,438.96
LCOE (NOK/MWh)	1,659.87	1,457.47	504.25	1,845.61

Table 15: Levelized cost of energy results for Tampen wind park, r = 7 %

	Unsubsidised	Subsidised (NOx-fund)	Subsidised (NOx and Enova)	Equinor (Subsidy from NOx-fund)
Total lifetime costs(NOK)	4,819,419,129.02	4,253,419,129.02	1,753,419,129.02	5,338,827,129.02
Total lifetime output(MWh)	3,479,801.78	3,479,801.78	3,479,801.78	3,479,801.78
LCOE (NOK/MWh)	1,384.97	1,222.32	460.42	1,534.23

The case being considered in the sensitivity analysis is the NO_X-fund subsidised case based on data from operating wind parks and reports referred to earlier in the text. Naturally, the LCOE is increasing linearly with increasing discount rate.

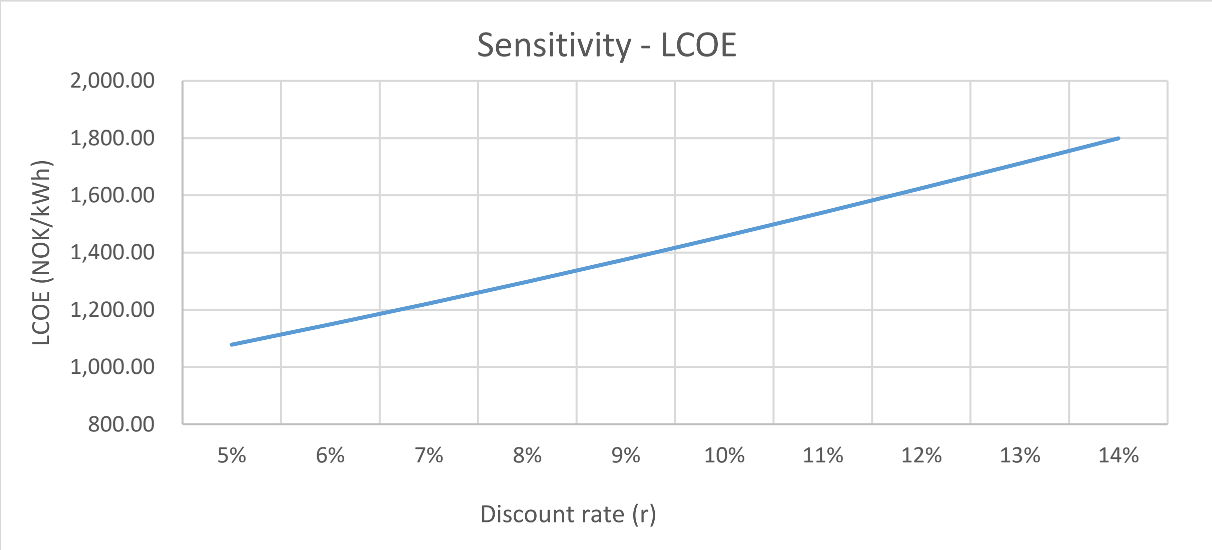


Figure 28: LCOE - discount rate sensitivity analysis

At a 10 % discount rate the levelized cost of energy is 1457 NOK/kWh with NOx-fund support.

4.2.1 Tampen Area Gas exports and gas prices

To calculate the NPV for Hywind Tampen an estimate is needed for the forward price of natural gas in Europe, how much the natural gas produced on Gullfaks and Snorre is worth. This is a necessary quantity to be able to calculate the reduced fuel cost F and will be an important input to the NPV equation.

It turns out that finding the price of natural gas, is not as easy as finding the price of a barrel for oil. The oil price is constantly displayed on the first page in all financial press. It takes less than 30 seconds to find the price of the north sea oil, Brent, and on the same page you can compare with the West Texas Intermediate oil (WTI). Natural gas on the other hand, is not as obvious.

Back to the gas price, why is the price of gas not as known as the price of Brent oil? In 2017 Norway exported gas worth over NOK 200 billion. As an oil exporter Norway has a relatively small percentage of the total world supply, but as a gas exporter Norway plays an important role. Especially within the European Union. About 25% of EU`s gas demand is supplied from Norway. Norwegian gas exports for 2017 are shown in the figure below.

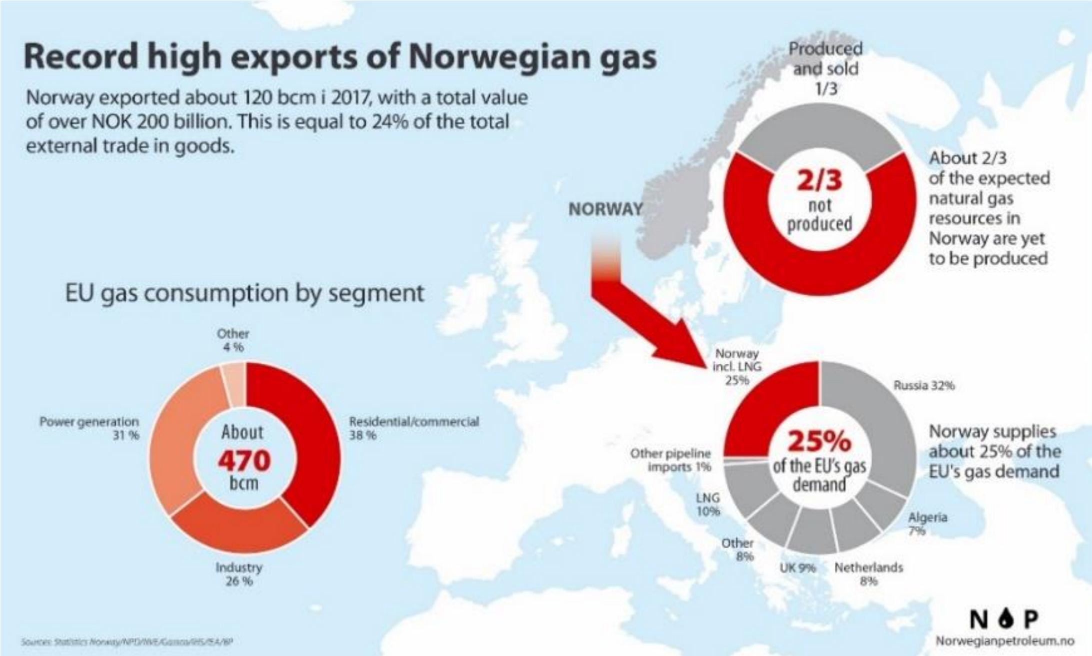


Figure 29: Norwegian gas export in 2017 [76]

One of the reasons that the gas price is not as visible as the oil price is that it requires a lot more infrastructure to be a gas exporter, and to be a gas importer as well. The value chain for oil is much more developed, with a lot more competition than the value chain for natural gas. There are petrol stations on every corner of the world, and there are many companies that import and sell diesel and gasoline, which is two of the large volume end products coming from crude oil. Both crude oil, diesel and gasoline are easily and cheaply transported worldwide to whoever pays the highest price for it.

Natural gas on the other hand are mostly exported through pipelines. In many cases from one exporter to one importer with customers having piping only to a monopolist seller. This is a simplification of course, many European gas companies has the option to get gas from more than one supplier, but still they are much more limited than the exporters and retailers of crude oil are.

So, where does the gas from Gullfaks and Snorre field end up, and approximately how much do Equinor get payed for it? The Gullfaks field is connected to a branch of the "Statpipe Rikgass", which is a 30" pipeline that sends gas to Kårstø gas terminal in Rogaland. Other producing fields producing gas to the Statpipe Rikgass 30" pipeline is Gullfaks Sør, Gimle, Tordis, Vigdis and Visund. At Kårstø there are separation facilities for separating the wet gases such as propane and butane out of the gas before the dry natural gas is exported through a pipeline ending up in Emden Germany. [77]. The situation is the same for the is also the case for Snorre gas. Statpipe to Kårstø. [78]

There is also a gas export pipeline from Gullfaks to Statfjord field ending up in UK. This is called the Tampen Link. Occasionally, e.g. in case of revision maintenance stops at Kårstø, gas from Tampen can be directly exported to UK [79]. It is possible for both Snorre and Gullfaks to export gas to both continental Europe and UK.

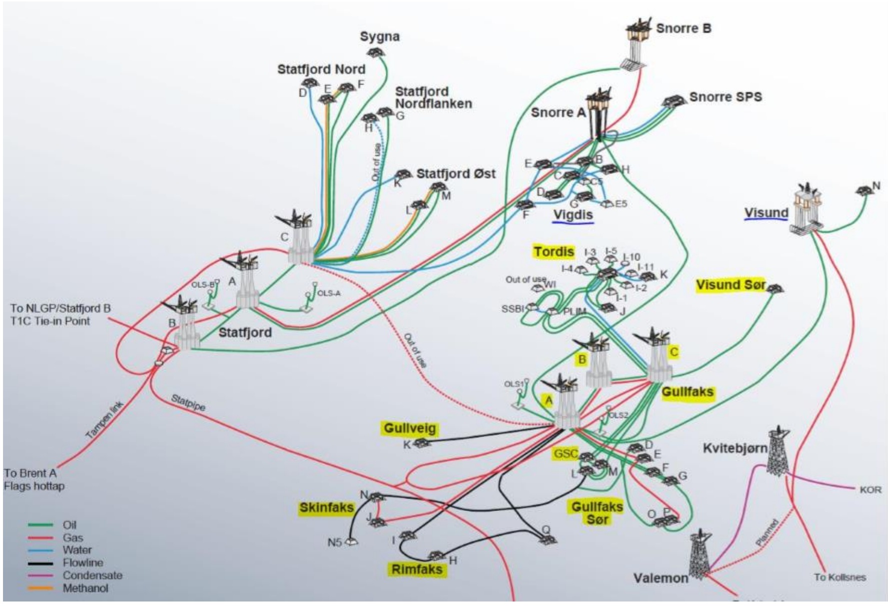


Figure 30: Overview of Tampen area [80]

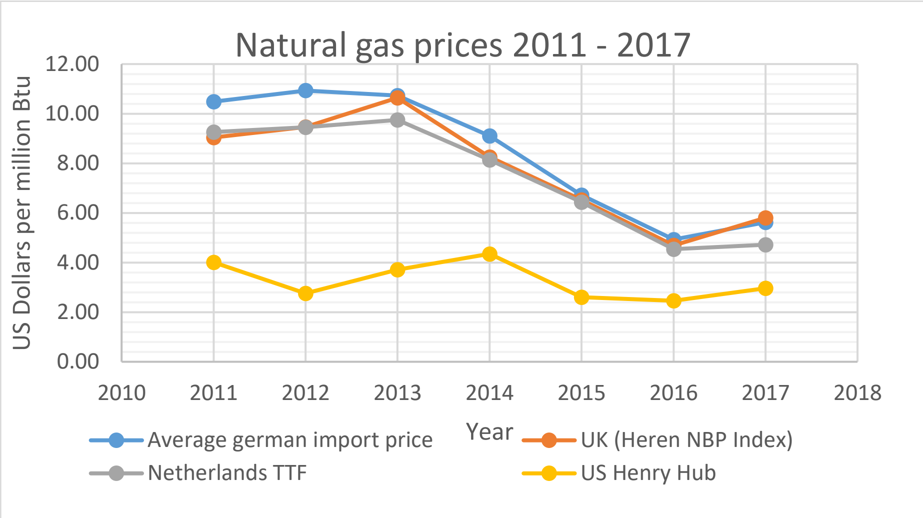
Where the gas export pipelines end up is of importance to this paper, because gas is not priced the same in Emden Germany as it is for instance in St. Fergus UK. And gas is certainly not priced the same in Europe as in the US.

In this paper, data was first used from the June Edition of "BP Statistical Review of World Energy" [81] as input to calculate average European gas price from 2011 to 2017. By using the average of NBP Index, average German import price and the Netherlands TTF from 2011 through 2017, the result was an average European gas price of 7.87 USD/MBtu.

In 2017 the oil and gas industry faced a worldwide downturn. In 2011 the prices were sky high. Historically the prices of farm level commodities such as oil and gas have high variance. What will be the correct estimated price of natural gas in Europe in the future? This is very difficult to estimate and could have been the theme of a master's degree thesis itself.

The initial plan was to us the average historical European gas price from 2011 – 2017 in this thesis. An average price of 7.87 USD/MBtu was calculated based on collected data. This price is the average of NBP Index, the average German import price, and average of t the Netherlands TTF between 2011 and 2017 taken from "BP Statistical Review of World Energy" 67 edition, published in June 2018. It was assumed that this would give a reasonable estimate. The prices at Henry HUB in Louisiana US, are also shown at the bottom to illustrate the large regional differences in gas price. Henry HUB gas prices are around half of European gas prices.

Figure 31: Overview – European gas prices, 2011-2017



Another important aspect with regards to what Equinor gets paid for their gas is that the prices we have are based on dry gas import prices. On the Kårstø plant, the heavy fractions of gas coming from the North Sea through the “Statpipe Rikgass” such as Butane and Propane are withdrawn from the natural gas and sold separately. Therefore Equinor gets more money for the gas than what the average dry gas European prices indicate. In this thesis we haven’t looked into gas transport tariffs, or % of Tampen gas sold as richgas and to what prices. That could have been a thesis on its own. From now we just make the assumption that the increase in transport tariffs are cancelled by the rich gas income.

After some consideration we realized that using historical prices for natural gas was probably not the most accurate approach. By switching our searches to forward gas prices, instead of gas prices and historical gas prices we were able to find the World Bank Natural Gas Price forecast up to year 2030. It is likely that the World Bank has better statistical models than us, so we decided that instead of basing our estimate on historical prices of 7.87 USD/MMBtu, the World Bank Natural Gas Price forecast should be used.

The world bank list forward gas prices both in “nominal US dollars” and in “constant US Dollars”, since we haven’t got any information regarding future inflation and development of OPEX Costs, CO2 Tax, NOx Tax and cycling costs, we decided to keep all prices in real terms, and hence use gas prices in constant US dollars.

An average forward gas price from 2019-2039 was considered, until we realized that we couldn’t find forward currency exchange rates further than 1 year. Therefore, to be consistent, the gas price used is the price forecast for 2019 in “constant US Dollars”: 5.4 $/mmBtu, and likewise all currency exchange rates used are 1 year forward – for November 2019 [82]. We also see below that the gas forecast is relatively flat in constant US dollars.

Table 16: World Bank Natural Gas Price forecast [83] in (constant US dollars)

Year	2018	2019	2020	2021	2022	2023	2024	2025	2030
Natural gas, Europe, constant US dollars ($/mmBtu)	5.3	5.4	5.5	5.6	5.7	5.9	6.0	6.1	6.6

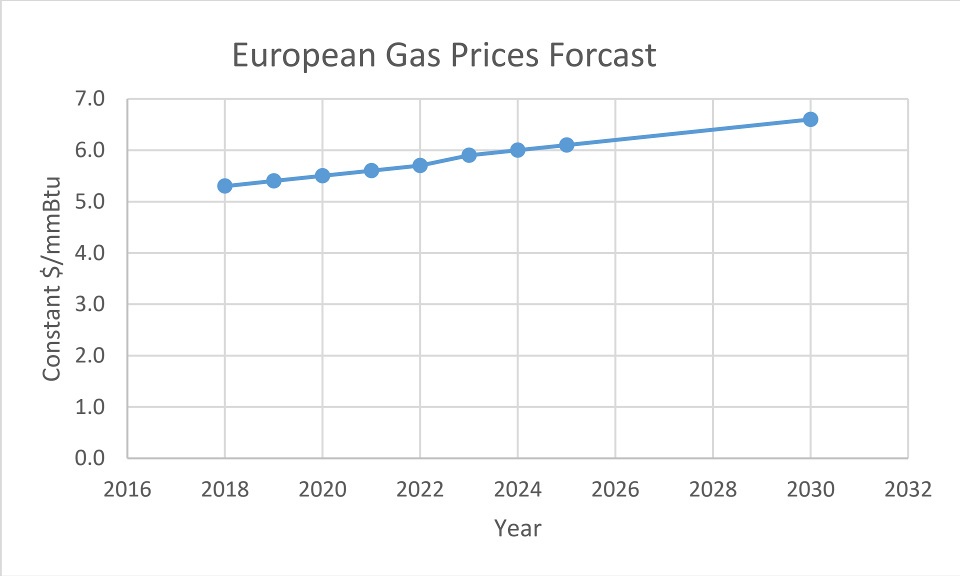


Figure 32: World Bank Natural Gas Price forecast up to year 2030 [83]

So for the rest of this thesis an estimated forward gas price of 5.4 USD/MMBtu will be used, for all years up to 2042.

Data for how much oil and gas that is produced from each individual field on NCS are publicly available information on the pages of the Norwegian petroleum directorate. Data has been extracted from Snorre [84], and Gullfaks [85] and plotted them together below.

What seems to be the case is that the gas production from Gullfaks and Snorre has been decreasing since the end of the 1990s. As shown in Figure 33 below, the Gullfaks field has not had saleable gas production since 2010, while Snorre still has some, but very little compared to the 1990s.

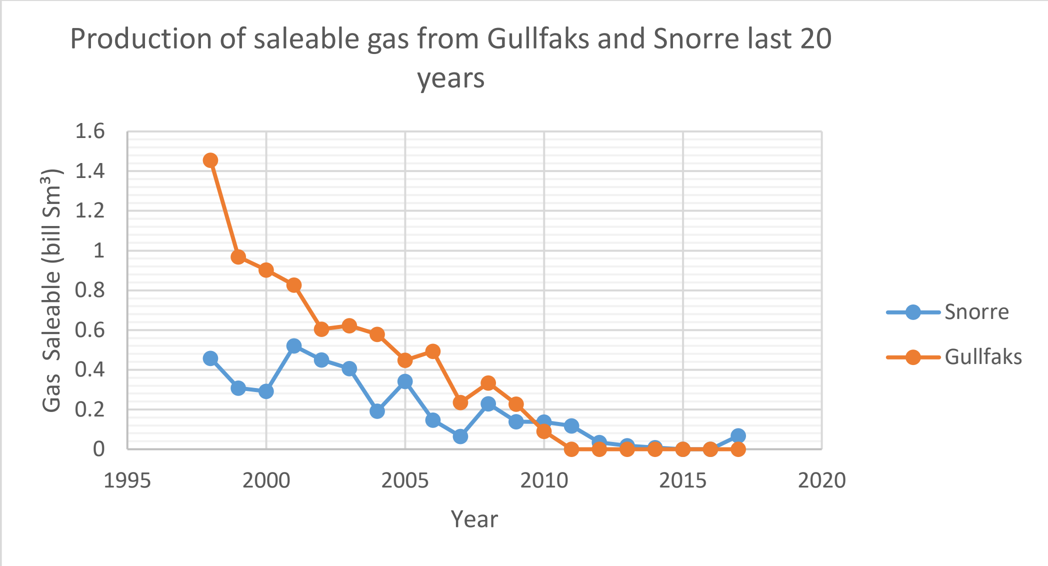


Figure 33: The figure shows decreasing production of saleable gas from Gullfaks and Snorre.

A question is, does Gullfaks and Snorre produce enough gas to supply their own fuel gas, or is the situation that Gullfaks and Snorre have to start using diesel, commercially traded as Marine Gas Oil (MGO) to generate electricity on the platforms? MGO is a refined product that the platforms gets supplied from shore, and it is a more valuable and expensive fuel.

4.2.2 Consumption of fuel gas and diesel for Gullfaks and Snorre

By analysing the data for consumption of diesel and fuel gas on each individual field in the reports that operators on NCS each year has to send to “Miljødirektoratet”, the total consumption of diesel and fuel gas can be seen.

These reports are made annually per field. Gullfaks submits their report [86], and Snorre submits their [87]. The reports are open information, and when knowing what to look for a lot of information can be extracted. In this thesis, the reports have been used extensively for the years 2011 -2017 to extract data on the following subjects:

- Gross consumed fuel gas
- Consumption diesel

From these data, the annual consumption of both fuel gas and diesel can be seen. Sadly there are only available data back to 2011. Preferably, data all the way back to the 1990s would have been available. From this “Årsrapport to Miljødirektoratet” the annual consumption of both fuel gas and diesel for Gullfaks and Snorre can be seen.

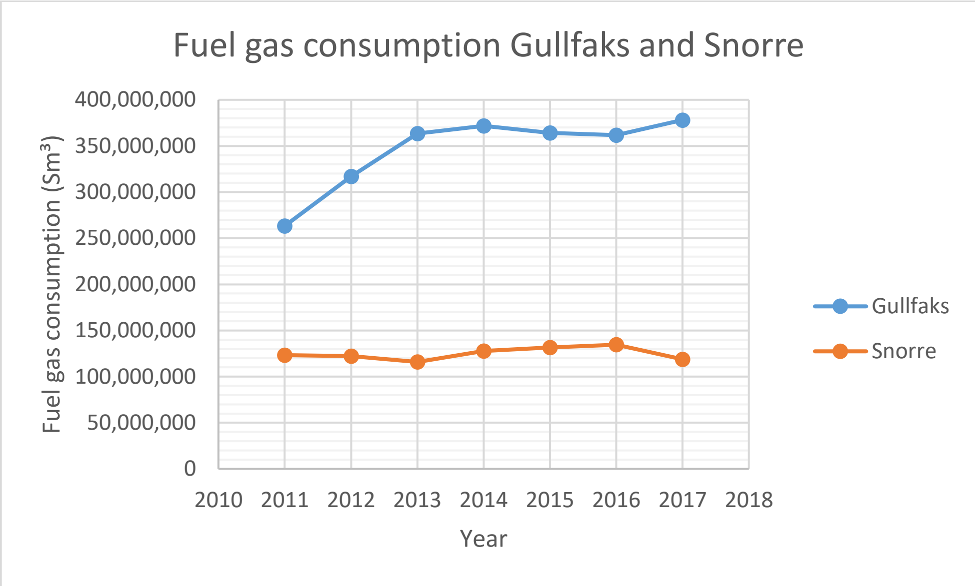


Figure 34: Fuel gas consumption – Gullfaks and Snorre

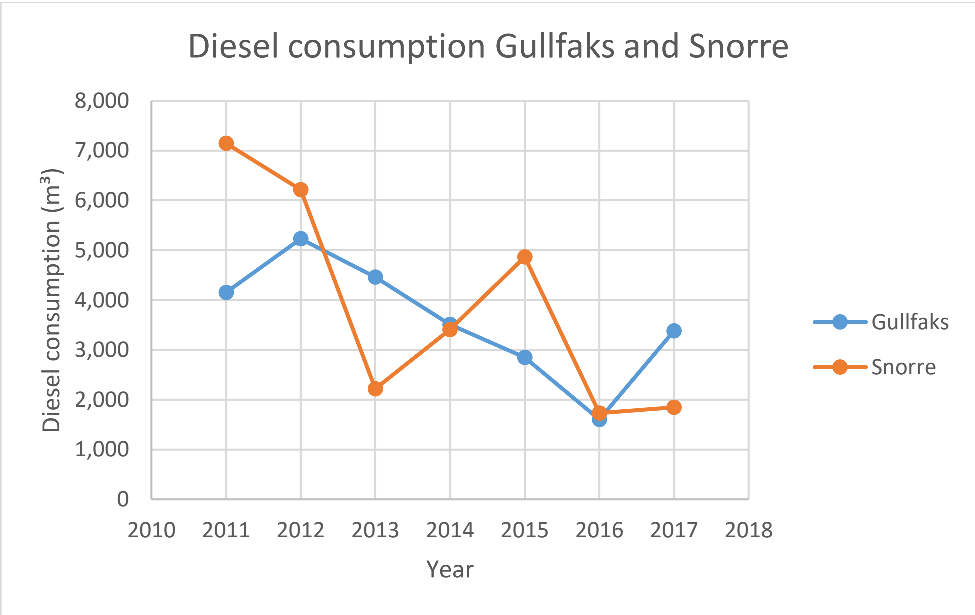


Figure 35: Diesel consumption – Gullfaks and Snorre

From the data above a calculation can be made for the total amount of greenhouse gases emitted, but that is not the topic of this theses. The object is to make a NPV calculation of alternative 1, go ahead with the Hywind Tampen project, or alternative 2, to continue using diesel and fuel gas for generation of electricity onboard the platforms on Gullfaks and Snorre.

In order to do this, digging deeper into the data is needed. The reason is that not all the fuel gas and diesel that is burned are used for generating electricity. Some gas and diesel are also used for direct mechanical operation of gas injection compressors and gas export compressors. And the Hywind Tampen project cannot supply these machines. So they need to be kept out of the equation.

From the publicly open information on the pages of the Norwegian petroleum directorate, and in the annual reports to “Miljødirektoratet”, the total consumption of fuel gas and diesel can be read, and the total saleable gas production, but which of the gas turbines that are used for electricity production and which turbines that are used for mechanical drive applications of compressors, is not specified.

4.3 Generation of electricity on Gullfaks and Snorre

So the the total consumption of fuel gas and diesel on Gullfaks and Snorre fields is known. What is not known, is how much of the diesel and fuel gas consumed that actually is used for power generation, and how much that is used for other purposes.

After some research an overview on the pages of the Norwegian Petroleum Directorate was found, that was published back in 2013. It is named “Oversikt over motorer og turbiner” [8]. This spreadsheet provides an overview of all the internal combustion engines, flairs, boilers, gas turbines, and other machinery emitting CO2 and NOx on NCS, and it is very detailed. It hasn’t been updated since 2013. Naturally, an overview from 2017 would have been preferred, but this is not available, possibly because the Norwegian Petroleum Directorate do not possess a newer one either. However, it is not likely that it has been large changes between 2013 and 2018 for installations built in the 1980`s and 1990`s. The authors have attempted to get this kind of detailed information from operators regarding thermal efficiencies, fuel and gas consumptions, but have not succeeded in this.

By translating to English, and by further processing the available spreadsheet data, calculations for the annual power generation on each field in MWh/year are made. In Table 17 and Table 18 below results from these calculations are shown.

Gullfaks annual power generation:

Table 17: Annual generation of electricity on Gullfaks. Based on a further developed "Oversiktsskjema for motorer og turbiner" [8]

Inst.	Turbin Modell	Type [Gass/ Diesel/ Dual]	Use	Total Cap [MW]	Normal Load [MW]	Load [%]	Given efficiency [%]	Normal efficiency [%]	Total Ops time [timer]	Annual Power consumption [MWh]
GFA	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFA	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFA	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFA	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFC	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFC	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
GFC	LM2500 PE	Dual	Power	23	14	61%	37	37	4000	56,000
Total annual generation of electricity on Gullfaks in									**[MWh]**	**392,000**

For the Snorre field the annual generation of electricity looks like this:

Table 18: : Total annual generation of electricity on Snorre. Based on a further developed "Oversiktsskjema for motorer og turbiner" [8]

Inst.	Turbin Model	Type [Gas/ Diesel/ Dual]	Use	Total Cap [MW]	Normal Load [MW]	Load [%]	Given efficiency [%]	Normal efficienc y [%]	Total Ops time [timer]	Annual Power consumption [MWh]
SNA	LM 2500 PE	Dual	Kraft	22	14	64%	37	34.8	6570	91,980
SNB	LM 2500 +	Dual	Kraft	30	17	57%	45.8	40	7446	126,582
SNA	LM 2500 PE	Dual	Kraft	22	14	64%	37	34.8	6570	91,980
SNA	LM 2500 PE	Dual	Kraft	22	14	64%	37	34.8	6570	91,980
SNB	LM 2500 +	Dual	Kraft	30	17	57%	45.8	40	7446	126,582
Total annual generation of electricity on Snorre in								**[MWh]**		**529,104**

4.3.1 Energy mix for Gullfaks and Snorre

As one can read from the table above, the turbines intended for generation of electrical power are of dual fuel type. Diesel is much more expensive than fuel gas. So in order to make a valid estimation of fuel expenditures F, an estimation for how many % of the annual power production that is fuelled by diesel, and how much that is fuelled by gas, has to be made. Furthermore, an estimation for the price of diesel, or Marine Gas Oil (MGO) which is the commercial name for diesel fuel traded in bulk for marine and offshore use, has to be made.

When converting the total amount of fuel gas used, and MGO used for Gullfaks to energy in MJ it is clear that the installations are almost exclusively using fuel gas. Of its total energy consumption Gullfaks gets 1% from diesel, and 99% from gas. Snorre gets around 3% from diesel and 97% from gas.

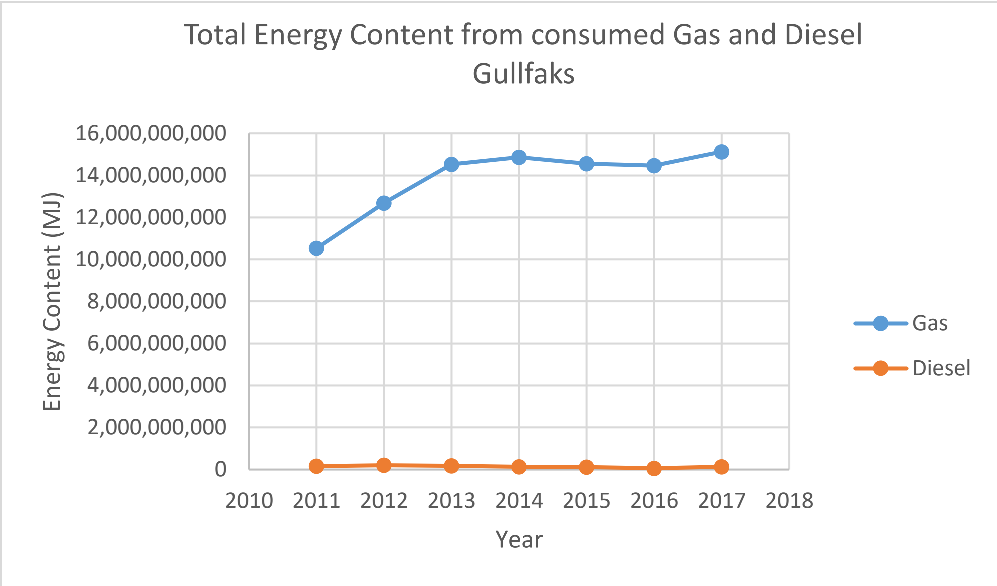


Figure 36: Total Energy Content from consumed gas and diesel - Gullfaks

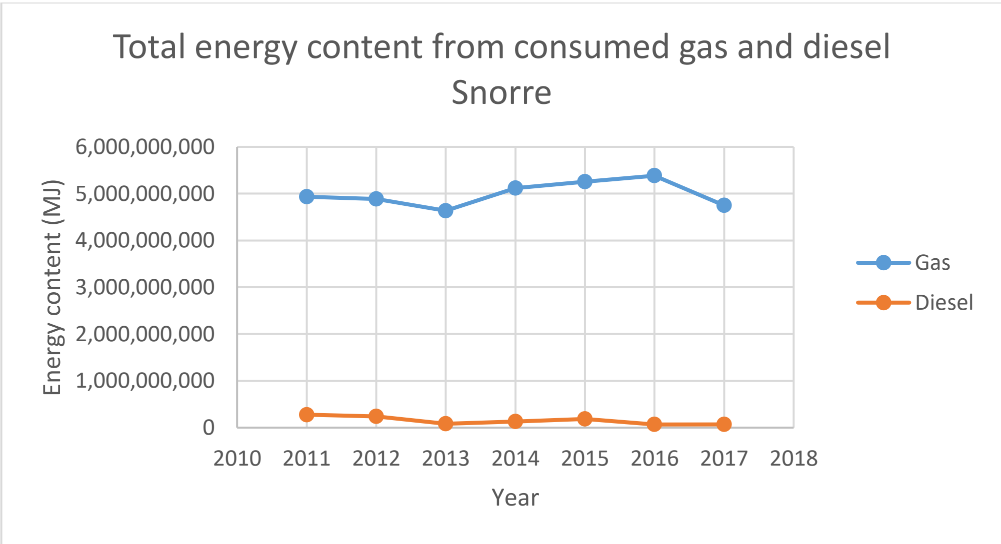


Figure 37: Total energy content from consumed gas and diesel - Snorre

The accuracy of the actual consumption data for the part of the fuel used for power generation dates back to 2013, so the calculations can be simplified by just assuming that power generation on Gullfaks and Snorre is done 100% by fuel gas.

When we saw the declining production curve for saleable gas from Gullfaks and Snorre, we started to wonder if it was such a shortage of gas in the Tampen area that Gullfaks and Snorre had shifted to power generation from MGO. Some research was done to find a valid MGO price as input to our NPV calculation in case we found out that MGO was used extensively for power production. So for the sake of completeness we will in the next subchapter give our estimated expected price for MGO in USD/Ton and, also calculate an expected price in USD/MJ to compare with. Hywind Tampen has an estimated lifetime of 20 years, and before 20 years have passed, we might be in a situation where the gas pressure also on the surrounding satellite fields are so depleted that Equinor at some point will have to shift from gas to MGO for power generation.

4.3.2 Price of MGO, and prices in USD/MJ for gas and MGO

Equinor has an oil refinery at Mongstad outside Bergen. All the MGO that Equinor intends to consume offshore, they will presumably purchase from themselves. But at what price? For several reasons this is not an easy question to answer accurately. When purchasing internally, what price does Equinor have to pay? And what costs shall we add for transportation to the platform with supply vessels? There are many unknown factors involved. The price of MGO has traditionally been highly correlated to the price of crude oil. In the future it will still be correlated to the price of crude oil, but an extra factor to consider now is that there is a lot of speculation to a future rise in MGO prices. This is due to a possible ban of fuels with Sulphur content > 0.5%, for ships not having a scrubber installed. If this ban becomes a reality it may lead to a dramatic price increase for MGO which is the alternative for ships without scrubber installed.

As a result, when estimating the price for MGO, we have chosen to use the World BIX average for MGO between 2011 and 2017. With the same arguments as we used for gas price. 2011 had unusually high prices, 2017 probably had unusually low prices. We are aware that Equinor probably can purchase MGO cheaper than world average price from 2011-2017, but that is a part of the opportunity cost discussion. If Equinor did not use the MGO from their Mongstad refinery offshore, they could have sold it on the world market. (and they do). So we decided to use the world BIX index averaged annually in the period between 2011 and 2017. We collected data for all months from 2011 through 2017 for the BIX index, which is the average MGO price for all the major ports in the world [88]. This should give an estimate for the MGO price. So in the cases where we need to use diesel price for future calculations we will use the price USD 852.93 /MT.

Table 19: Average price of MGO from 2011-2017

Date	*Price $/MT*	*+/-*	*Low*	*High*
Average 2017 - 2011	852.93	-0.08	612.67	1252.12

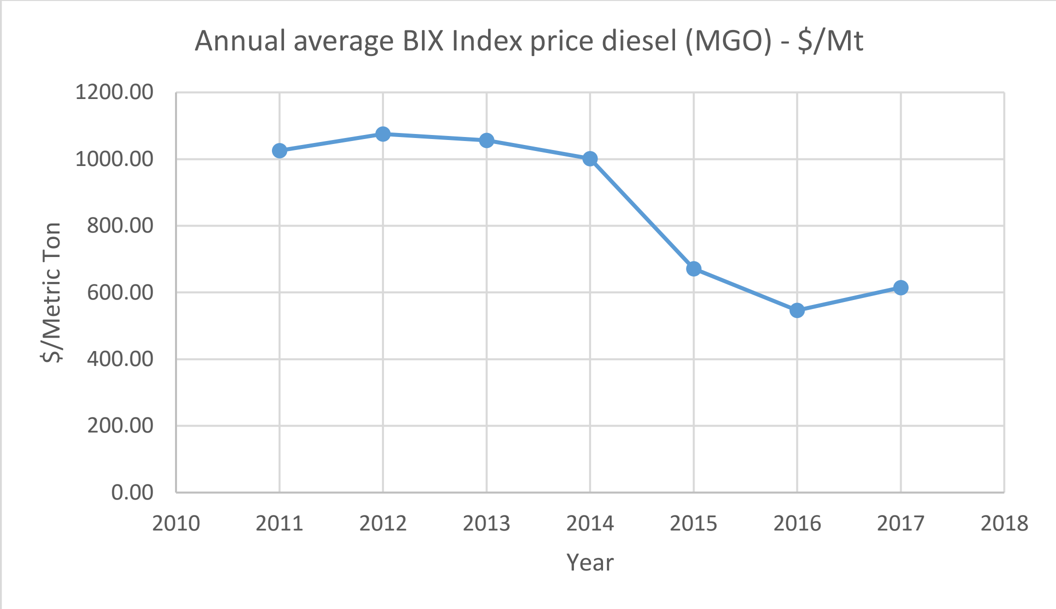


Figure 38: BIX index average price of MGO from 2011-2017

If it had turned out that Marine Gas Oil was an important part of the Tampen energy mix we would have to find the 10 year + forward MGO prices as well. However, since diesel only accounts for 1% and 3% of the energy mix on Gullfaks and Snorre this will only have a neglectable influence on the results.

4.3.3 Price of fuel gas and diesel in $/MJ

When analysing the data, and discovering that Gullfaks gets 99% of its energy from fuel gas. Furthermore that Snorre gets 97% of its energy from fuel gas, we suspect a relatively large price difference between fuel gas and diesel. And perhaps not so surprising, we see that when calculating price per MJ, we get that the price of diesel per MJ of energy is more than twice as high as the price of gas per MJ of energy.

Table 20: Price of marine gas oil and natural gas in USD/MJ

Diesel	*Price $/MT*		Price $/MJ
Average price 2011-2018 BIX MGO	841.26		0.018695
Energy content MGO	45,000	MJ/Ton	
Natural Gas	Pris $/Mbtu		Price $/MJ
World Bank gas forcast price 2019 [82]	5.40		0.0051185
Conversion factor: 1 Btu =	0.001055	MJ	

4.3.4 Calculation of the price of annual power consumption on Gullfaks and Snorre

So finally, we are arriving at one of the key questions. What is fuel expenditures on Gullfaks and Snorre in 2017? If Equinor`s decision is to approve the Hywind Tampen project, how large will annual savings be from:

- Fuel gas that can be sold instead of burned?
- Reduction in CO2 tax?
- Reduction in NOx tax?

For the Gullfaks field, 100% usage of fuel gas for power generation is assumed, and 0% usage of diesel for generation of electricity the calculations looks like this, when using data from "Oversikt over motorer og turbiner" [8]. Note that GFA, GFC and SNA all has Heat rate 9,169 Btu /kWh equivalent to efficiency factor of 37 %, [8]. while SNB has heat rate of 7,450 Btu/kWh equivalent to 45,8%. [8]. This is due to the combined cycle on SNB. [89]

For the USD/NOK exchange rate this paper uses the 1year forecast price from DNB [82]. Ideally we should have the 10 or 15 years forward price. But this is currently not available to us.

Annual fuel costs for Gullfaks, without CO2 and NOx tax, if 100% of the fuel comes from gas is shown in Table 21 below and for Snorre in Table 22.

Table 21: Annual fuel costs for Gullfaks A & Gullfaks C without CO_2 and NO_x tax. Based on a further developed "Oversiktsskjema for motorer og turbiner" [8]

Inst.	Turbin Modell	Norm load [MW]	Ops. hrs [h]	Annual power consumpt [kWh]	Gross heat rate, LHV [Btu/kWh]	Fuel Gas Consumpt. [Btu]	Fuel Gas Consumpt. [MBtu]	Fuel Gas Consumpt. [Sm³]	World Bank forcast price of Eurpean Gas [$/MBtu]	Annual price if 100% Nat. Gas for fuel [$]
GFA	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFA	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFA	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFA	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFC	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFC	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
GFC	LM2500 PE	14	4000	56,000,000	9,169	5.13464E+11	513,464	14,539,956	5.4	2,772,706
				392,000,000						
The value of cons. Fuel gas on Gullfaks annually									USD	19,408,939
						cf	8.09			
The value of cons. Fuel gas on Gullfaks annually									NOK	157,018,318
				Fuel cost Gullfaks in a world without CO2 and Nox tax					NOK/kWh	0.40055693

Table 22: Annual fuel costs for Snorre A without CO_2 and NO_x taxes Based on a further developed "Oversiktsskjema for motorer og turbiner". [8]

Inst.	Turbin Modell	Norm load [MW]	Ops. hrs [h]	Annual power consumpt [kWh]	Gross heat rate, LHV [Btu/kWh]	Fuel Gas Consumpt. [Btu]	Fuel Gas Consumpt. [MBtu]	Fuel Gas Consumpt. [Sm³]	World Bank forcast price of Eurpean Gas [$/MBtu]	Annual price if 100% Nat. Gas for fuel [$]
SNA	LM 2500 PE	14	6570	91,980,000	9,169	8.43365E+11	843,365	23,881,877	5.4	4,554,169
SNA	LM 2500 PE	14	6570	91,980,000	9,169	8.43365E+11	843,365	23,881,877	5.4	4,554,169
SNA	LM 2500 PE	14	6570	91,980,000	9,169	8.43365E+11	843,365	23,881,877	5.4	4,554,169
				275,940,000						
The value of cons. Fuel gas on Snorre A annually									USD	13,662,507
						cf	8.09			
The value of cons. Fuel gas on Snorre A annually									**NOK**	110,529,680
				Fuel cost Snorre A in a world without CO2 and NOx taxes					**NOK/kWh**	0.400556934

Annual fuel costs for Snorre A without CO_2 and NO_x taxes. Based on a further developed "Oversiktsskjema for motorer og turbiner". [8]

Inst.	Turbin Modell	Norm load [MW]	Ops. hrs [h]	Annual power consumpt [kWh]	Gross heat rate, LHV [Btu/kWh]	Fuel Gas Consumpt. [Btu]	Fuel Gas Consumpt. [MBtu]	Fuel Gas Consumpt. [Sm³]	World Bank forcast price of Eurpean Gas [$/MBtu]	Annual price if 100% Nat. Gas for fuel [$]
SNB	LM 2500 +	17	7446	126,582,000	7,450	9.43008E+11	943,008	26,703,518	5.4	5,092,243
SNB	LM 2500 +	17	7446	126,582,000	7,450	9.43008E+11	943,008	26,703,518	5.4	5,092,243
				253,164,000						
The value of cons. Fuel gas on Snorre B annually									USD	10,184,487
						cf	8.09			
The value of cons. Fuel gas on Snorre B annually									**NOK**	82,392,500
				Fuel cost Snorre A in a world without CO2 and NOx taxes					**NOK/kWh**	0.325451089

4.3.4.1 CO2 Taxes on NCS

On the NCS all operators have to pay a carbon tax of 1,06 kr/Sm³ for each Sm³ of natural gas that gets burned [89]. In Norway in general there is a tax of 21.94 kr/kg for each kilogram of NOx that is emitted [90]. First, with only CO_2 tax added, the picture looks like this for the Snorre and Gullfaks platforms:

Table 23: Annual fuel cost for Gullfaks A/C CO_2-tax included, NOx-tax excluded [8].

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price if 100% Nat. Gas for fuel [$]	Price pr Sm³ consumpt. [NOK/ Sm³]	Annual Price of CO2 Tax [NOK]	Annual Price of CO2 Tax [$]	Annual cost including CO2 Tax [$]
GFA	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFA	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFA	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFA	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFC	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFC	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
GFC	LM2500 PE	56,000,000	14,539,956	2,772,706	1.06	15,412,353	1,905,112	4,677,817
TOT		392,000,000	101,779,691	19,408,939		107,886,472	13,335,781	32,744,721
cf	8.09		IN NOK	157,018,318				
Cost of CO2 emissions at gullfaks						NOK/kWh	0.275220592	
Fuel cost Gullfaks including CO2 Tax. (No NOx tax)						NOK	264,904,790	
Fuel cost Gullfaks including CO2 Tax. (No NOx Tax)						NOK/kWh	0.675777526	

Table 24: Annual fuel cost for Snorre A, CO_2-tax included, NOx-tax excluded [8].

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price if 100% Nat. Gas for fuel [$]	Price pr Sm³ consumpt. [NOK/ Sm³]	Annual Price of CO2 Tax [NOK]	Annual Price of CO2 Tax [$]	Annual cost including CO2 Tax [$]
SNA	LM2500 PE	91,980,000	23,881,877	4,554,169	1.06	25,314,790	3,129,146	7,683,315
SNA	LM2500 PE	91,980,000	23,881,877	4,554,169	1.06	25,314,790	3,129,146	7,683,315
SNA	LM2500 PE	91,980,000	23,881,877	4,554,169	1.06	25,314,790	3,129,146	7,683,315
TOT		275,940,000	71,645,632	13,662,507		75,944,370	9,387,438	23,049,944
cf	8.09		IN NOK	110,529,680				
Cost of CO2 emissions at Snorre A						NOK/kWh	0.275220592	
Fuel cost Snorre A including CO2 Tax. (No NOx tax)						NOK	186,474,051	
Fuel cost Snorre A including CO2 Tax. (No NOx Tax)						NOK/kWh	0.675777526	

Table 25: Annual fuel cost for Snorre B, CO_2-tax included, NOx-tax excluded [8].

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price if 100% Nat. Gas for fuel [$]	Price pr Sm³ consumpt. [NOK/ Sm³]	Annual Price of CO2 Tax [NOK]	Annual Price of CO2 Tax [$]	Annual cost including CO2 Tax [$]
SNB	LM2500 +	126,582,000	26,703,518	5,092,243	1.06	28,305,730	3,498,854	8,591,098
SNB	LM2500 PE	126,582,000	26,703,518	5,092,243	1.06	28,305,730	3,498,854	8,591,098
TOT		253,164,000	53,407,037	10,184,487		56,611,459	6,997,708	17,182,195
cf	8.09		IN NOK	82,392,500				
Cost of CO2 emissions at Snorre B						NOK/kWh	0.223615756	
Fuel cost Snorre B including CO2 Tax. (No NOx tax)						NOK	139,003,959	
Fuel cost Snorre B including CO2 Tax. (No NOx Tax)						NOK/kWh	0.549066845	

4.3.5 NOx Taxes on NCS, and total fuel expenditure F by installation on Tampen.

As mentioned earlier in the text, the NOx tax is not related to Sm³ of gas burned, or to ton of diesel burned. This is because there are several technologies available that is reducing the NOx content in the exhaust gases. Further, the authorities wishes to put in place incentives to reduce NOx emissions. Hence, NOx is taxed 21.94 kr/kg [90] for each kilogram of NOx that is actually emitted.

For Gullfaks A the emissions and the cost of emissions put together looks like this:

Table 26: Annual fuel cost for Gullfaks A, both NO_x and CO_2-tax included [8].

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price including CO2 Tax [$]	NOx-dis. f gas [g/Sm3] (PEMS / Nox Tool)	Nox emitted [kg]	Nox Tax [NOK / kg]	Nox Tax [NOK]	Nox Tax [$]	Annual cost incl CO2 and Nox Tax [$]
GFA	PE	56,000,000	14,539,956	4,677,817	8.7	126,498	21.94	2,775,358	343,060	5,020,878
GFA	PE	56,000,000	14,539,956	4,677,817	8.7	126,498	21.94	2,775,358	343,060	5,020,878
GFA	PE	56,000,000	14,539,956	4,677,817	8.7	126,498	21.94	2,775,358	343,060	5,020,878
GFA	PE	56,000,000	14,539,956	4,677,817	8.7	126,498	21.94	2,775,358	343,060	5,020,878
cf	8.09	224,000,000		18,711,269				11,101,431	1,372,241	20,083,510
Cost of NOx emissions at GFA									NOK/kWh	0.049560
Fuel cost GFA including CO2 and Nox Tax									NOK	162,475,597
Fuel cost GFA including CO2 and NOx Tax									NOK/kWh	0.725337

For Gullfaks C the emissions and the cost of emissions put together looks like this:

Table 27: Annual fuel cost for Gullfaks C, both NO_x and CO_2-tax included [8].

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price including CO2 Tax [$]	NOx-dis. f gas [g/Sm3] (PEMS / Nox Tool)	Nox emitted [kg]	Nox Tax [NOK / kg]	Nox Tax [NOK]	Nox Tax [$]	Annual cost incl CO2 and Nox Tax [$]
GFC	LM2500 PE	56,000,000	14,539,956	4,677,817	9.4	136,676	21.94	2,998,662	370,663	5,048,480
GFC	LM2500 PE	56,000,000	14,539,956	4,677,817	9.4	136,676	21.94	2,998,662	370,663	5,048,480
GFC	LM2500 PE	56,000,000	14,539,956	4,677,817	9.4	136,676	21.94	2,998,662	370,663	5,048,480
cf	8.09	168,000,000		14,033,452				8,995,987		15,145,440
Cost of NOx emissions at GFC									NOK/kWh	0.053548
Fuel cost GFC including CO2 and Nox Tax									NOK	122,526,611
Fuel cost GFC including CO2 and NOx Tax									NOK/kWh	0.729325

For Snorre A the emissions and the cost of emissions put together looks like this:

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price including CO2 Tax [$]	NOx-disc. F gas [g/Sm3]	Nox emitted [kg]	Nox Tax [NOK / kg]	Nox Tax [NOK]	Nox Tax [$]	Annual cost incl CO2 and Nox Tax [$]
SNA	LM2500 PE	91,980,000	23,881,877	7,683,315	11	267,477	21.94	5,868,446	725,395	8,408,710
SNA	LM2500 PE	91,980,000	23,881,877	7,683,315	11	267,477	21.94	5,868,446	725,395	8,408,710
SNA	LM2500 PE	91,980,000	23,881,877	7,683,315	11	267,477	21.94	5,868,446	725,395	8,408,710
cf	8.09	275,940,000		23,049,944				17,605,338		25,226,130
Cost of NOx emissions at SNA									NOK/kWh	0.063801
Fuel cost SNA including CO2 and Nox Tax									NOK	204,079,389
Fuel cost SNA including CO2 and NOx Tax									NOK/kWh	0.739578853

Table 28: Annual fuel cost for Snorre A, both NO_x and CO_2-tax included [8].

For Snorre B the emissions and the cost of emissions put together looks like this:

Inst.	Turbin Modell	Annual power consumpt [kWh]	Fuel Gas Consumpt. [Sm³]	Annual price including CO2 Tax [$]	NOx-disc. F gas [g/Sm3]	Nox emitted [kg]	Nox Tax [NOK / kg]	Nox Tax [NOK]	Nox Tax [$]	Annual cost incl CO2 and Nox Tax [$]
SNB	LM2500 +	126,582,000	26,703,518	8,591,098	34	897,238	21.94	19,685,407	2,433,301	11,024,399
SNB	LM2500 +	126,582,000	26,703,518	8,591,098	34	897,238	21.94	19,685,407	2,433,301	11,024,399
cf	8.09	253,164,000		17,182,195				39,370,813		22,048,798
Cost of NOx emissions at SNB									NOK/kWh	0.155515
Fuel cost SNB including CO2 Tax and NOx tax									NOK	178,374,772
Fuel cost SNB including CO2 Tax and NOx Tax									NOK/kWh	0.704582

Table 29: Annual fuel cost for Snorre B, both NO_x and CO_2-tax included [8].

4.3.6 Cycling costs for gas turbine powerplants

Naturally, when phasing renewable energy into power grids presently being powered by fossil fuel gas turbines the load pattern of the gas turbine is changing. The load is varying more, start and stops are more frequent and the average load percentage for each generator tend to be lower. The term used to describe this is “cycling”.

A Study has been conducted by the U.S. Department of Energy, by their national laboratory (NREL) to determine the impact of cycling on gas turbine generators. The findings are that starts and stops are more frequent leading to increased thermal stresses, premature failures and increased O&M costs.

With regards to increased O&M costs, the previously mentioned study concluded that “33% wind and solar penetration causes cycling costs to increase by $ 0.47 $1.28/MWh” [91]. If that is converted to NOK/kWh which is used in this thesis, the result is 0.0038023 NOK/kWh to 0.0103552 NOK/kWh, when using USD to NOK exchange rate of 8.09 Cycling costs are below 0.01 NOK/kWh, which is much less than expected, and a good indication as to how far todays modern world gas turbine manufactures has come with regards to fuel economy even under shifting loads. The mid interval between 0.0038023 NOK/kWh to 0.0103552 NOK/kWh will be used. Cycling costs are set to 0.0070788 NOK/kWh which is in the middle of the interval.

This phenomena was also confirmed by interview object no 2 [92] , who in particular mentioned thermal stresses and thus failures in the exhaust gas collectors of the LM 2500+ turbines in times of frequent start and stop. This is something to take into account, if it is deemed necessary to optimize the existing gas turbine generators for coexistence with HWT. On the drawing below we can see an exhaust gas collector of a General Electric LM 2500+ Gas turbine.

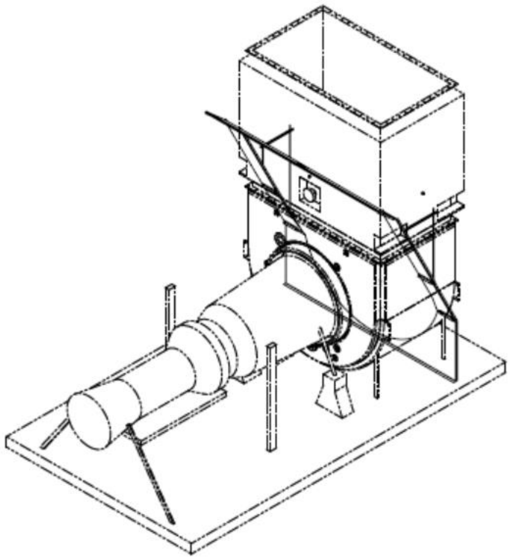


Figure 39: The exhaust gas collector of a GE LM 2500+ gas turbine

4.3.7 Annual savings from less used CO2 Quotas:

In addition to the CO2 tax, the operating companies on NCS has to pay a CO2 quota of NOK 54.91 (see Table 1) per ton CO2 emitted. This has a relative small effect on the price of power. Approximately 0,03344 NOK / kWh.

Table 30: The effects of CO_2-quotas on the price of power.

Input	QTY	Unit
Annual reduction in CO2 after HWT	200,000	ton
Price of 1 quota (1 ton) -2018	54.91	NOK/ton
Annual savings from red CO2 quotas	10,982,000	NOK
Annual Output HWT	328,468,670	kWh
Average price CO2 quota	0.03343393	NOK / kWh

4.4 LCOE for present day gas turbines on Gullfaks and Snorre.

To recap the expense part of the formula for LCOE looks like this:

$$\left(\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}\right) \tag{2.1a}$$

Where $I_t(initial\ investment\ costs)$, M_t, expenditures related to O&M in year t, and F_T are fuel expenditures in year t. The only expenditures in this case that are not sunk are the fuel costs. In the following chapter a thorough breakdown of the fuel expenditures for the four Tampen platforms with gas turbine power production today will be presented.

To illustrate better what the fuel expenditures on the Gullfaks and Snorre platforms are, an overview for total fuel expenditures is made, and divided by the actual power generation. This provides a number that many people can relate to. Most people know that they pay around 0.7 NOK / kWh for their electricity at home now in November, and around 1.40 NOK / kWh including all taxes and fees. Now the reader also know that the fuel expenditures are around 0.82 to 0.89 NOK/kWh for electricity generation offshore by use of gas turbines.

To be more precise, the fuel expenditures in this case vary from 75 øre/kWh at SNB to 78 øre/ kWh at SNA. Note that SNB has the lowest F_T in NOK / kWh due to the combined Jules-Brayton – Rankine cycle. On the other hand SNB has the highest NOx emission, so the savings from the high thermal efficiency are almost lost by the high NOx discharge and thus tax.

Inst.	Price of gas in [NOK/kWh] by Inst	Price of CO2 Tax [NOK / Sm3] by Inst	Annual price of NOX Tax by inst [NOK /	Cycling costs [NOK / kWh]	Price of CO2 Quotas [NOK / kWh]	Total Fuel Cost [NOK / kWh]
GFA	0.400556934	0.27522059	0.04956	0.007079	0.03343393	0.7659
GFC	0.400556934	0.27522059	0.0535475	0.007079	0.03343393	0.7698
SNA	0.400556934	0.27522059	0.0638013	0.007079	0.03343393	0.7801
SNB	0.325451089	0.22361576	0.1555151	0.007079	0.03343393	0.7451

Table 31: Total fuel expenditures for the platforms on Tampen

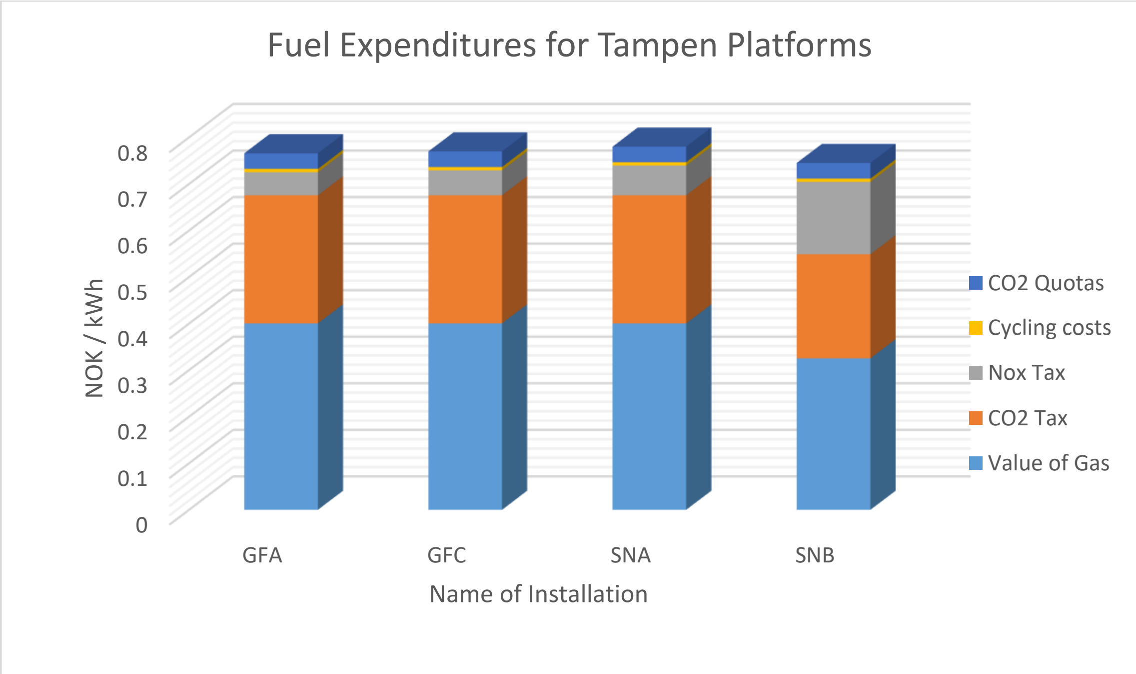


Figure 40: Graphical representation of the various cost elements in the total fuel expenditures

4.5 The overall power generation situation on Tampen

Our estimates show that the Gullfaks and Snorre platforms combined have an annual power production of 921.124 MW, and thus annual fuel expenditures of NOK 803,898 672 or NOK 804 million when CO2 and NOx taxes are included.

Inst.	Annual price of gas if 100% nat gas for fuel, pr inst [NOK]	Annual price of CO2 Tax pr inst [NOK]	Annual price of NOX Tax by inst [NOK]	Cycling costs by Inst [NOK]	Price of CO2 Quotas [NOK]	Total Fuel Cost [NOK]
GFA	89,724,753	61,649,413	11,101,431	1,662,109	7,489,201	164,137,706
GFC	67,293,565	46,237,060	8,995,987	1,246,582	5,616,901	123,773,193
SNA	110,529,680	75,944,370	17,605,338	2,047,511	9,225,759	206,126,899
SNB	82,392,500	56,611,459	39,370,813	1,878,510	8,464,268	180,253,282
Total						674,291,080

Table 32: Total annual fuel expenditures for the Gullfaks and Snorre fields

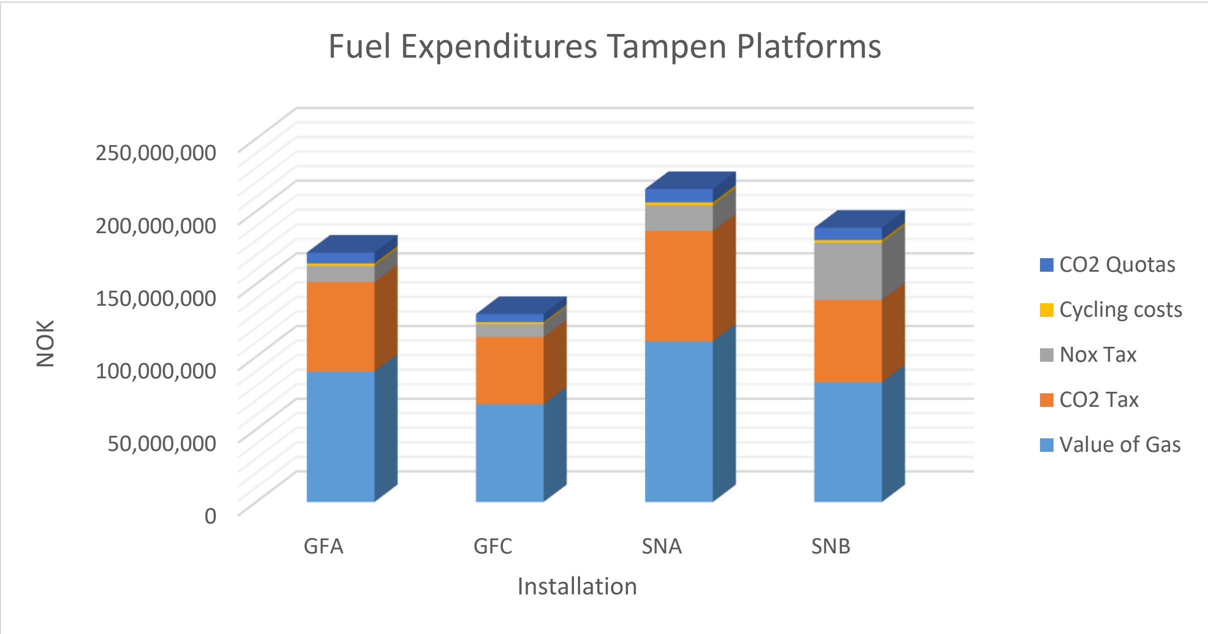


Figure 41: Graphical representation of the various cost elements in the total fuel expenditures

The interesting discovery from these results is the amount of gas generators that in average can be shut down when the power grids on Gullfaks and Snorre are connected with the HWT project. There will be large future savings from gas that can be sold instead of burned, and CO2 and NOx taxes that will not have to be paid. The question is of course if the savings from the reduced fuel expenditures will be large enough through the remaining lifetime of Snorre and Gullfaks, and the lifetime of HWT to justify the HWT project. Will the NPV be positive, or if negative, how much at a 10 % discount rate.

One could start with the question, how many gas turbine generators are running at one time at the Gullfaks and Snorre oilfields in our present situation? In other words before the HWT wind turbines are connected to the grids on the various platforms. At what load are they typically running? And how many can be shut down. And what are the difference in fuel costs F_T. After the ΔF_T are found we could input the this ΔF_T in the NPV calculation and discount it as future positive cashflow.

This is unnecessary time consuming, and complex, with large insecurities because. The load condition on power grids is not a static quantity, it is a dynamic quantity that varies depending on for instance how the process currently is running. Are we running water injection pumps? What drilling activities are currently ongoing? Are we drilling, tripping or logging? Are we drilling every year? Or in campaigns of 1 year or two years ? The questions are many, and the calculations become hopeless.

So the exact power usage for the various Gullfaks and Snorre platforms for the period 2018 - 2040 is not known to us. What we have is a report from 2013 that shows us running hours and normal load condition at the time.

Inst.	Turbin Model	Application	Total Cap. [MW]	Normal load [MW]	Load pct [%]	Given real eff. factor [%]	Norm. eff. factor [%]	Total Ops hrs [h]	Recovered heat [MW]	Number of online generators pr field	# of generators are discrete. Hence # of generators online	# of generators in Standby or stop
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	1.7	1.83	2.00	2
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	1.2			
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	2			
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	0			
GFC	LM2500 PE	Power	23	14	61%	37	37	4000	2.2	1.37	2	1
GFC	LM2500 PE	Power	23	14	61%	37	37	4000	1.2			
GFC	LM2500 PE	Power	23	14	61%	37	37	4000	0			
SNA	LM 2500 PE	Power	22	14	64%	37	34.8	6570		2.25	3	0
SNA	LM 2500 PE	Power	22	14	64%	37	34.8	6570				
SNA	LM 2500 PE	Power	22	14	64%	37	34.8	6570				
SNB	LM 2500 +	Power	30	17	57%	45.8	40	7446	5	0.85	1	1
SNB	LM 2500 +	Power	30	17	57%	45.8	40	7446	5			
Overall situation Tampen			287	174							8	4

Table 33: Load situations and operation hours for the Tampen area [8]

So we do not know exactly how much load there will be on the generators from 2018 until 2040. But we do know the heat rates for the LM 2500+ turbines. And we have calculated the fuel expenditures F_T for each generator including CO2 and NOx tax.

This is actually enough for us to calculate the saved fuel costs. Because as the reader has seen in the previous chapter we have calculated the cost of producing in NOK / kWh. And when we in the next chapter have been able to calculate the annual output from HWT based on wind data from Tampen we know how much power is produced by HWT. Then the saved annual fuel cost $F_{T-Saved}$ will simply be

$$F_{T-Saved} = Annual\ output\ HWT\ [kWh] * fuel\ cost\ in\ \left[\frac{NOK}{kWh}\right] \tag{4.1}$$

4.6 Annual wind production from Hywind Tampen

By using extrapolated wind data from e-Klima we have been able to calculate a likely annual production figure from HWT.

Below is the Weibull distribution created from the measured wind data where the average wind speed is 8.2 m/s. This is beneath the nominal wind speed of the turbines which reaches full effect first at 13 m/s.

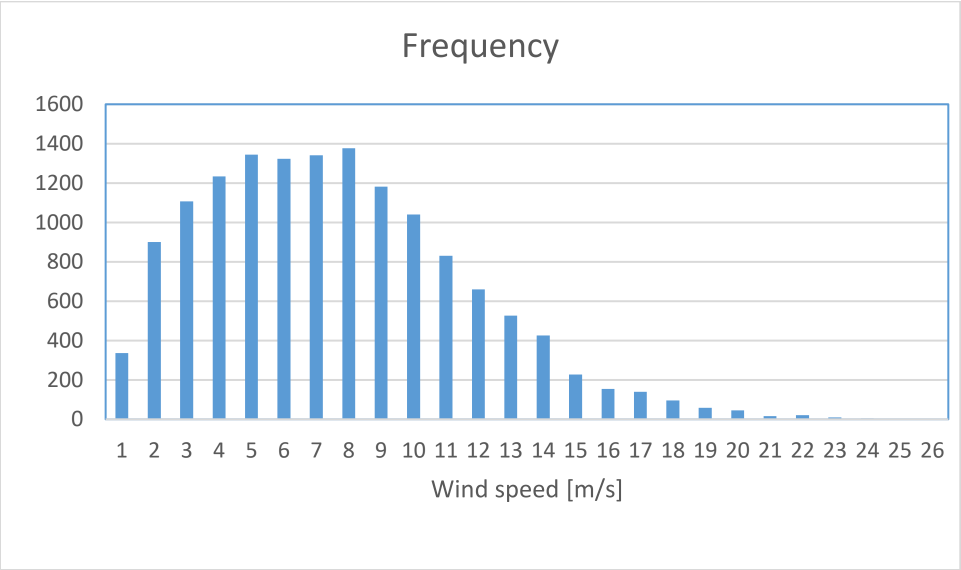


Figure 41: Weibull frequency distribution of wind speeds measured at Gullfaks C

There is little difference in the measured values at 80 metres and extrapolated values at 100 metres as seen in the graph below.

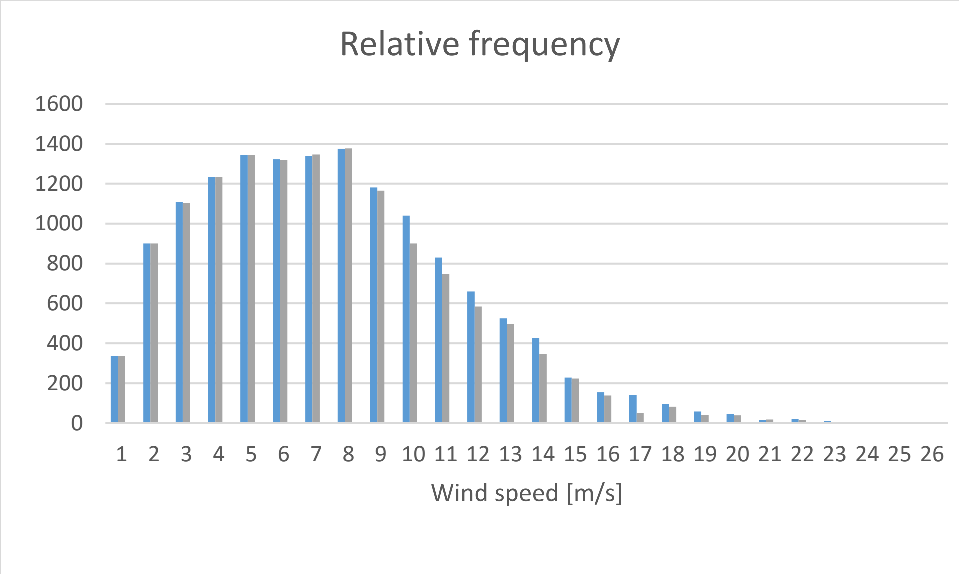


Figure 42: Weibull relative frequency distribution of wind speeds measured at Gullfaks C. Grey bars at 80 metres and blue bars at 100 metres.

Table 34: Calculated annual output from Hywind Tampen

Speed [m/s]	hrs/yr	Output [kWh/yr]	
1	275.49	0	
2	465.13	0	
3	606.05	0	
4	701.68	70,168	
5	754.93	490,702	
6	770.19	885,717	
7	753.36	1,393,719	
8	711.28	2,062,702	
9	651.07	2,701,945	
10	579.59	3,245,715	
11	502.93	3,570,818	
12	426.13	3,323,810	
13	353.03	2,824,216	
14	286.27	2,290,187	
15	227.43	1,819,439	
16	177.15	1,417,167	
17	135.36	1,082,915	
18	101.53	812,255	
19	74.79	598,300	
20	54.12	432,964	
21	38.49	307,929	
22	26.91	215,305	
23	18.51	148,044	
24	12.52	100,133	
25	8.33	66,637	
26	5.46	0	
	8760	29,860,788	kWh/turbine

A further development of the data above gives this picture, when we know that HWT has 11 turbines.

Table 35: Annual power production by HWT and typical output

Measure	Quantity	Unit
Annual production HWT	29,860.79	MWh/turbine
No of tubines HWT	11	ea.
Annual prod HWT total	328,468.67	MWh
Annual average production	37.50	MW

From this we can see that our annual average savings are estimated to the fuel expenditures F_T needed to generate 328,468.67 MWh. Since we already know the fuel cost in NOK/kWh, the calculations are relatively straight forward. But first, one important detail: Heat recovery from gas turbines on Gullfaks and Snorre.

4.7 Heat recovery from Snorre and Gullfaks turbines

As mentioned before the exhaust gases still contain substantial amounts of energy after leaving the gas turbines. According to the General Electric datasheet the temperature is over 500°C, and the remaining exhaust energy is 175 MM Btu / hr [42]. It is very common to have waste heat recovery systems in place on both ships with engines over a certain size, and on oil production platforms. The question in the case of HWT is, when stopping a number of generators, will the platforms still produce enough steam to cover heat needs through the Waste Heat Recovery Systems.

If too many gas turbines are shut down we might be in a situation where we are saving fuel gas for the generators, but we might end up having to generate steam through gas fired boilers or run the gas turbines at lower load to produce enough steam to have enough for heating purposes that are essential for the process as well as for the living quarters. Let us have a look at which gas turbines that has waste heat recovery systems installed today.

Inst.	Turbin Model	Application	Total Cap. [MW]	Normal load [MW]	Load pct [%]	Given real eff. factor [%]	Norm. eff. factor [%]	Total Ops hrs [h]	Recovered heat [MW]	Stopped turbines - norm. load [MWh]
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	1.7	
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	1.2	
GFA	LM2500 PE	Power	23	14	61%	37	37	4000	2	
~~GFA~~	~~LM2500 PE~~	~~Power~~	~~23~~	~~14~~	~~61%~~	~~37~~	~~37~~	~~4000~~	~~0~~	14
GFC	LM2500 PE	Power	23	14	61%	37	37	4000	2.2	
GFC	LM2500 PE	Power	23	14	61%	37	37	4000	1.2	
~~GFC~~	~~LM2500 PE~~	~~Power~~	~~23~~	~~14~~	~~61%~~	~~37~~	~~37~~	~~4000~~	~~0~~	14
~~SNA~~	~~LM 2500 PE~~	~~Power~~	~~22~~	~~14~~	~~64%~~	~~37~~	~~34.8~~	~~6570~~		14
~~SNA~~	~~LM 2500 PE~~	~~Power~~	~~22~~	~~14~~	~~64%~~	~~37~~	~~34.8~~	~~6570~~		14
~~SNA~~	~~LM 2500 PE~~	~~Power~~	~~22~~	~~14~~	~~64%~~	~~37~~	~~34.8~~	~~6570~~		14
SNB	LM 2500 +	Power	30	17	57%	45.8	40	7446	5	
SNB	LM 2500 +	Power	30	17	57%	45.8	40	7446	5	
Overall situation Tampen			287	174						70

Table 36: Present load situation and operation hours for the Tampen area [8].

We can see that on GFA all except one gas turbine has WHRU system installed and in use. In the spreadsheet above we have highlighted in yellow the generators we suggest shutting down. On GFC 2/3 gas turbine generators has WHRU system installed and in use. In the case of SNA none of the gas turbine generators has a WHRU system installed. In the case of SNB both of the gas turbine generators has not only a WHRU system installed, they actually have a combined Brayton-Rankine cycle with a thermal efficiency of 45.8%, which is highest on NCS. [93]

From this we can see that we are able to shut down up to 70 MW of gas turbine power without worrying about not generating enough steam for heating purposes.

To reach 70MW without worrying about steam generation we must assume that SNA are allowed to shut down all gas turbine generators. This will most likely be the subject of technical safety studies within Equinor. But as we see it Snorre A could shut down all gas turbine generators, because SNA after HWT installation has cable to both SNB and to HWT main grid.

If we take one more look at the annual power production from HWT, and then we consider all wind turbines instead of just one, then the situation looks like this:

Table 37: Annual power production from HWT as function of wind speed

Speed [m/s]	hrs/yr	Output [kWh/yr]	No of turbines	Output [MWh/yr]	Output [MWh]	% of year	% of year with load < 70MW
1	275.49	0	11	0	0	3.14	0.00
2	465.13	0	11	0	0	5.31	0.00
3	606.05	0	11	0	0	6.92	0.00
4	701.68	70,168	11	772	1	8.01	0.00
5	754.93	490,702	11	5,398	7	8.62	0.00
6	770.19	885,717	11	9,743	13	8.79	0.00
7	753.36	1,393,719	11	15,331	20	8.60	0.00
8	711.28	2,062,702	11	22,690	32	8.12	0.00
9	651.07	2,701,945	11	29,721	46	7.43	0.00
10	579.59	3,245,715	11	35,703	62	6.62	0.00
11	502.93	3,570,818	11	39,279	78	5.74	5.74
12	426.13	3,323,810	11	36,562	86	4.86	4.86
13	353.03	2,824,216	11	31,066	88	4.03	4.03
14	286.27	2,290,187	11	25,192	88	3.27	3.27
15	227.43	1,819,439	11	20,014	88	2.60	2.60
16	177.15	1,417,167	11	15,589	88	2.02	2.02
17	135.36	1,082,915	11	11,912	88	1.55	1.55
18	101.53	812,255	11	8,935	88	1.16	1.16
19	74.79	598,300	11	6,581	88	0.85	0.85
20	54.12	432,964	11	4,763	88	0.62	0.62
21	38.49	307,929	11	3,387	88	0.44	0.44
22	26.91	215,305	11	2,368	88	0.31	0.31
23	18.51	148,044	11	1,628	88	0.21	0.21
24	12.52	100,133	11	1,101	88	0.14	0.14
25	8.33	66,637	11	733	88	0.10	0.10
26	5.46	0	11	0	0	0.06	0.00
	8760	29,860,788				100	28

What we see is that HWT produces more than 70 MW in 28% of the year. When the Gullfaks and Snorre platforms receive more than 70 MW per year it will have a negative impact on the steam generation from the WHRU systems.

4.8 Reduced steam generation capacity – how large of problem is this?

Based on our 2013 numbers that probably aren't very accurate is looks like that when output from HWT exceeds 70MW it has a negative impact of heat generation, which is needed for other purposes. The exact analyses of how much steam is needed on Snorre and Gullfaks is not part of this thesis. But we recommend that the following approach is used:

- Verify the amount of heat needed
- If 70 MW is the limit before heat production is negatively impacted:
  - one solution could be to reduce the number of wind mills from 11 to 9, so the total output is around 70 MW
  - another could be improvement of WHRU systems,

5 Results

In this thesis the authors seek to bring clarity to the plant economics of the power production on the Gullfaks and Snorre platforms of today, and if Hywind Tampen are set in production.

- In the first model we have calculated the lifetime expenses of HWT discounted at 10% discount rate. And the LCOE of Hywind Tampen
- In the second model we have calculated the lifetime expenses of the current power production solution on Gullfaks and Snorre Platforms.
- In the third model we have joined the two together to make a NPV model of the HWT project to make an advice to the decision makers if the project should be approved or not from a strictly plant economic point of view.
- In the fourth, fifth model we have included subsidies from NOx fund and Enova.
- In the final modelø we have made a NPV calculation with all subsidies and Equinors own CAPEX estimate of 5 billion NOK.

5.1 Lifetime expenses HWT, and LCOE of HWT

Annual prod pr one HWT turbine	29,860,790	kWh			
No of HWT Turbines	11	ea			
Total Annual output HWT	328,468,690	kWh			
Discount rate	10%				
HWT CAPEX	3,914,592,000	NOK			
HWT OPEX	85,409,280	NOK		(years 3-18 hidden)	
Year	0	1	2	19	20
HWT CAPEX (NOK)	3,914,592,000				
HWT OPEX (NOK)		77,644,800	70,586,182	13,965,100	12,695,545
Sum discounted OPEX	727,137,348	NOK			
Sum of HWT cost over lifetime (fuel savings excluded)	**4,641,729,348**	**NOK**			
HWT Annual output discounted at 10% d.r.		298,607,900	271,461,727	53,707,256	48,824,778
HWT Total output discounted at 10% d.r.	2,796,439,122	kWh			
LCOE of HWT Tampen (fuel savings excluded)	**1.6599**	**NOK/kWh**			

Remaining lifecycle cost of existing solution for power generation on Tampen:

As mentioned before the purchase and installation of the gas turbines on Tampen are sunk costs. So is also to a large degree also the Operation and Maintenance expenditures in year t. This because most of the spares are already bought, and the turbines has to be maintained and ready when the wind does not blow. So the only remaining expenditure that can be adjusted from now and until end of life is the Ft, the Fuel expenditures.

So when calculating the differential cash flow and the LCOE for the remaining lifetime of gas turbines on Tampen, we only need to account for the fuel expenditures.

Annual power production that will be shut down in case of HWT	328,468,690				
Total fuel expenditures	0.765218559	NOK / kWh			
Tampen annual savings from reduced fuel expenditures	251,350,338	(Ctrl)			
Discount rate	10%			(years 3-18 hidden)	
Year	0	1	2	19	20
Annual discounted Fuel Expenditures Tampen		228,500,307	207,727,552	41,097,789	37,361,626
Sum discounted fuel expenditures (annual savings)	2,139,887,114	NOK			
Gas turbine output annual output that will be replaced by HWT disc. At 10%		298,607,900	271,461,727	53,707,256	48,824,778
Gas turbine output annual output that will be replaced by HWT disc . At 10%	2,796,439,122	kWh			
LCOE of Excisting Power Production on Tampen	**0.7652**	**NOK/kWh**			

With regards to the LCOE Calculations the formula is used:

$$LCOE = \frac{Sum\ of\ cost\ over\ lifetime}{Sum\ of\ El.Energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (2.1)$$

Where:

I_t: *Investment expenditures in year t.*

M_t: *Operattion and maintenace expenditures in year t.*

F_t: *Fuel expenditures in the year t.*

r: *discount rate*

n: *the expected lifetime*

NPV of Hywind Tampen with no subsidies:

The estimated annual output from HWT is 328 468, 67 MWh. This is approximately 35% of the annual power generation that takes place on Tampen today.

When giving our advice to the decision makers all we really have to do is to calculate the annual savings from a 328 468, 67 MWh reduction in power generation by gas turbines multiplied with the cost of production which in this case is $F_{T\ Average}$ for GFA, GFC, SNA and SNB which is 0.765219 NOK/kWh, and feed this into a NPV model with an appropriate discount rate

These savings must then be compared with our estimated OPEX and CAPEX for HWT, discounted in the same model.

As mentioned before based on our data, which is from 2013, the decision makers should consider to go down to 70 MW, which would be 9 wind turbines instead of 11, to avoid problems with reduced steam generation from Waste Heat Recovery Units. At least they need to make calculations based on updated data to verify if this is a potential problem or not. The HWT Project would be even less efficient if the installation of 11 wind turbines leads to not enough steam production from WHRU, and then not enough steam to use for heating purposes in the production. Which again may lead to having to burn gas or diesel in boilers to generate steam.

The conclusion is that with 10% discount rate and our estimated CAPEX = NOK 3,914,592,00 and an OPEX of NOK 85,409,280 the NPV will be negative with NOK – 2,501,842,233

Annual prod pr one HWT turbine	29,860,790	kWh			
No of HWT Turbines	11	ea			
Total Annual output HWT	328,468,690	kWh			
Discount rate	10%				
HWT CAPEX	3,914,592,000	NOK			
HWT OPEX	85,409,280	NOK			
Annual power production that will be shut down in case of HWT	328,468,690				
Total fuel expenditures	0.765218559	NOK / kWh			
Tampen annual savings from reduced fuel expenditures	251,350,338	(Ctrl)		(years 3-18 hidden)	
Year	0	1	2	19	20
HWT CAPEX (NOK)	3,914,592,000				
HWT OPEX (NOK)		77,644,800	70,586,182	13,965,100	12,695,545
Sum discounted OPEX	727,137,348	NOK			
Sum of HWT cost over lifetime (fuel savings excluded)	**4,641,729,348**	**NOK**			
Year	0	1	2	19	20
Annual discounted Fuel Expenditures Tampen		228,500,307	207,727,552	41,097,789	37,361,626
Sum discounted Fuel expenditure savings	**2,139,887,114**	**NOK**			
NPV of the Hywind Tampen Project	**-2,501,842,233**	**NOK**			

NPV of Hywind Tampen with NOx Fund Subsidies:

The NOx subisdies are already granted. We haven't got any information regarding when the 566 MNOK from the NOx fund will be paid to Equinor, so for the sake of simplicity we have entered it in year 0.

Annual prod pr one HWT turbine	29,860,790	kWh			
No of HWT Turbines	11	ea			
Total Annual output HWT	328,468,690	kWh			
Discount rate	10%				
HWT CAPEX	3,914,592,000	NOK			
HWT OPEX	85,409,280	NOK			
Annual power production that will be shut down in case of HWT	328,468,690				
Total fuel expenditures	0.765218559	NOK / kWh			
Tampen annual savings from reduced fuel expenditures	251,350,338	NOK			
Discount rate	10%				
Year	0	1	2	19	20
HWT CAPEX (NOK)	3,914,592,000				
HWT OPEX (NOK)		77,644,800	70,586,182	13,965,100	12,695,545
Sum discounted OPEX	727,137,348	NOK			
Sum of HWT cost over lifetime (fuel savings excluded)	**4,641,729,348**	**NOK**			
Year	0	1	2	19	20
Annual discounted Fuel Expenditures Tampen		228,500,307	207,727,552	41,097,789	37,361,626
Sum discounted Fuel expenditure savings	**2,139,887,114**	**NOK**			
Subsidies from Nox Fund	**566,000,000**				
NPV of the Hywind Tampen Project	**-1,935,842,233**	**NOK**			

NPV of Hywind Tampen with 2.5 Billion Subsidies from ENOVA:

Positive NPV at CAPEX 3.9 Billion NOK (the authors estimate), if ENOVA subsidies are granted.

Annual prod pr one HWT turbine	29,860,790	kWh			
No of HWT Turbines	11	ea			
Total Annual output HWT	328,468,690	kWh			
Discount rate	10%				
HWT CAPEX	3,914,592,000	NOK			
HWT OPEX	85,409,280	NOK			
Annual power production that will be shut down in case c	328,468,690				
Total fuel expenditures	0.765218559	NOK / kWh			
Tampen annual savings from reduced fuel expenditures	251,350,338	NOK			
Discount rate	10%			(years 2-18 hidden)	
Year	0	1	2	19	20
HWT CAPEX (NOK)	3,914,592,000				
HWT OPEX (NOK)		77,644,800	70,586,182	13,965,100	12,695,545
Sum discounted OPEX	727,137,348	NOK			
Sum of HWT cost over lifetime (fuel savings excluded)	**4,641,729,348**	**NOK**			
Year	0	1	2	19	20
Annual discounted Fuel Expenditures Tampen		228,500,307	207,727,552	41,097,789	37,361,626
Sum discounted Fuel expenditure savings	**2,139,887,114**	**NOK**			
Subsidies from Nox Fund	**566,000,000**				
Subsidies from ENOVA	**2,500,000,000**				
NPV of the Hywind Tampen Project	**564,157,767**	**NOK**			

NPV of HWT with 2,5 Billion NOK Enova Subsidies at Equinor's own CAPEX estimate:

Annual prod pr one HWT turbine	29,860,790	kWh			
No of HWT Turbines	11	ea			
Total Annual output HWT	328,468,690	kWh			
Discount rate	10%				
HWT CAPEX	5,000,000,000	NOK			
HWT OPEX	85,409,280	NOK			
Annual power production that will be shut down in case c	328,468,690				
Total fuel expenditures	0.765218559	NOK / kWh			
Tampen annual savings from reduced fuel expenditures	251,350,338	NOK			
Discount rate	10%			(hears 2 -18 hidden)	
Year	0	1	2	19	20
HWT CAPEX (NOK)	5,000,000,000				
HWT OPEX (NOK)		77,644,800	70,586,182	13,965,100	12,695,545
Sum discounted OPEX	727,137,348	NOK			
Sum of HWT cost over lifetime (fuel savings excluded)	**5,727,137,348**	**NOK**			
Year	0	1	2	19	20
Annual discounted Fuel Expenditures Tampen		228,500,307	207,727,552	41,097,789	37,361,626
Sum discounted Fuel expenditure savings	**2,139,887,114**	**NOK**			
Subsidies from Nox Fund	**566,000,000**				
Subsidies from ENOVA	**2,500,000,000**				
NPV of the Hywind Tampen Project	**-521,250,233**	**NOK**			

5.2 Abatement costs for Hywind Tampen

Two types of abatement costs are calculated in this thesis. One is calculated where the saved fuel costs are accounted for as alternative cost. This case is a special case for this project and this must be kept in mind when comparing with other independent projects where there are no alternative costs. A more general case is also calculated where the saved fuel costs are not accounted for, but this means that there are no positive income on the cash flow. The most correct estimate for comparing with other green energy projects, may be the estimates where the fuel costs are included because alternative costs are normally considered in those. Klimakur 2020 released a report with abatement costs for different projects. In this report, they considered alternative costs as well [1]. However, when comparing with the EU ETS price fuel costs are excluded. The Klimakur 2020 report is from 2010 and considered to old to use for comparison with HWT.. In the table below These two cases are calculated with the authors' own CAPEX estimate of 3.914 billion NOK, as well as with Equinor's estimate of 5 billion NOK. They are presented in a sensitivity analysis with discount rates from 5-14% in the table below. In Klimakur 2020 a 5 % discount rate is used.

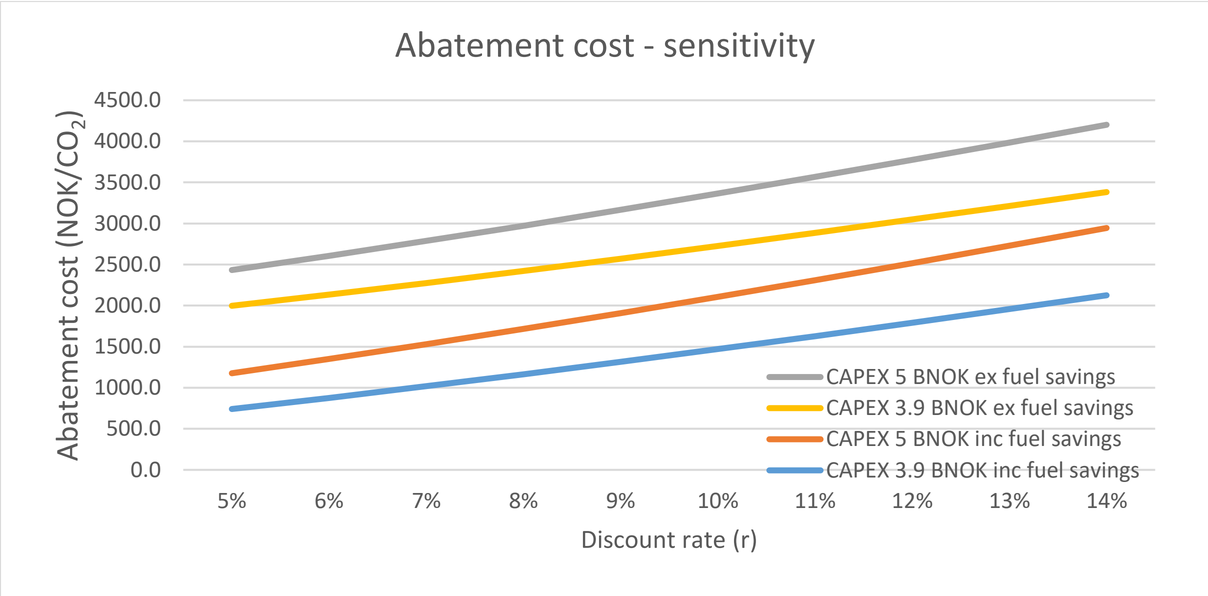


Figure 43: Sensitivity analysis for abatement costs

6 Conclusion

From a strict plant economical point of view, we cannot recommend going ahead with the HWT project, this because NPV is negative by 2.5 Billion NOK.

Furthermore, if the HWT project is realized we are replacing electricity that currently is generated at NOK 0.77 NOK/ kWh by electricity that will be generated at a LCOE of 1.66 NOK /kWh. And from a strict plant economical point of view this is not recommendable.

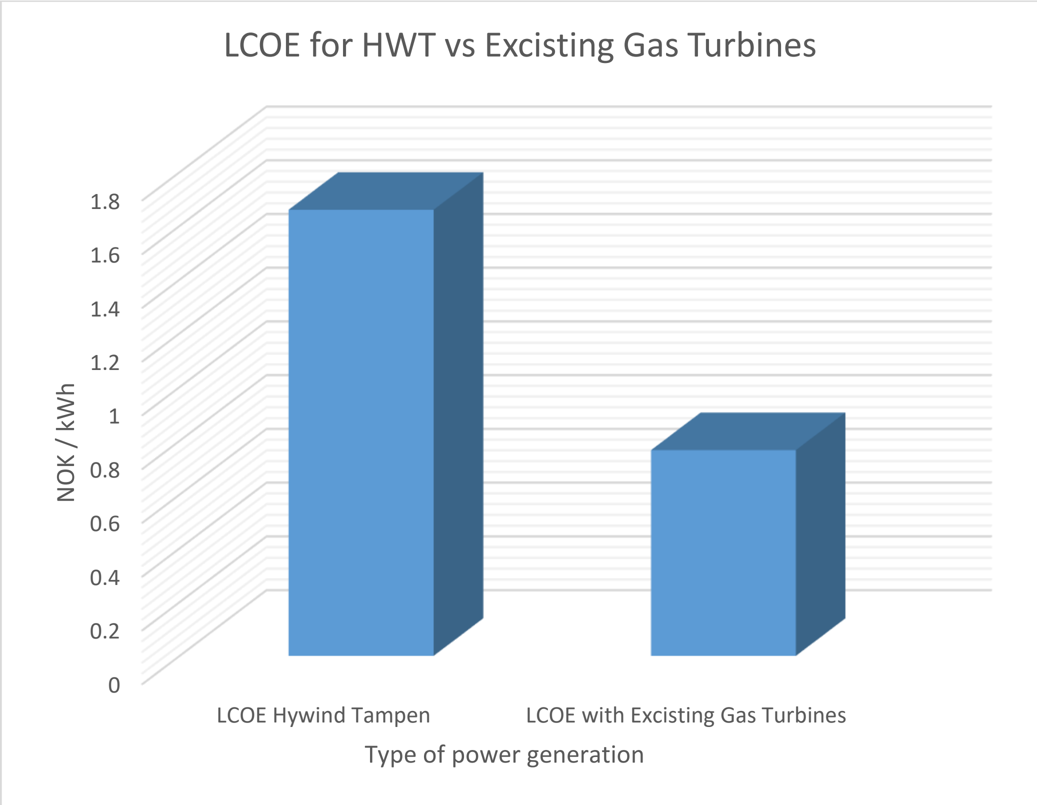


Figure XX LCOE Hywind Tampen vs LCOE of existing gas turbine generators.

Even with a negative NPV, the Equinor executive management might decide to go ahead with Hywind Tampen due to other positive effects such as:

- Equinor considers HWT a R&D project that the firm is willing to invest in to gain competency for future projects.
- HWT will give Equinor a "greener profile" which undoubtedly is positive in the Norwegian political climate of today. This may in turn give easier access to new areas for petroleum development.

Both of the above arguments are beyond the scope of this thesis and will not be further evaluated. In this thesis we analyse HWT strictly from a plant economical point of view.

As presented on the graph below HWT has a negative NPV of – 2.5 billion NOK without subsidies and under the current (2018) tax regime, when our estimated CAPEX of 3.9 billion NOK is used.

If the already approved HWT subsidies from the NOx fund are included, and they are paid in year 0, and the CAPEX of 3.9 billion NOK still is used the NPV is still negative at – 1.9 billion NOK.

If the 2.5 billion ENOVA subsidies are approved, and paid in year 0, if a CAPEX of 3.9 billion NOK still is used the NPV is actually positive at plus 564 MNOK.

Finally, if Equinor's own HWT CAPEX estimate at 5.0 billion NOK is used, and Enova and NOx fund subsidies are approved and paid in year 0, the NPV will be negative at – 521 MNOK.

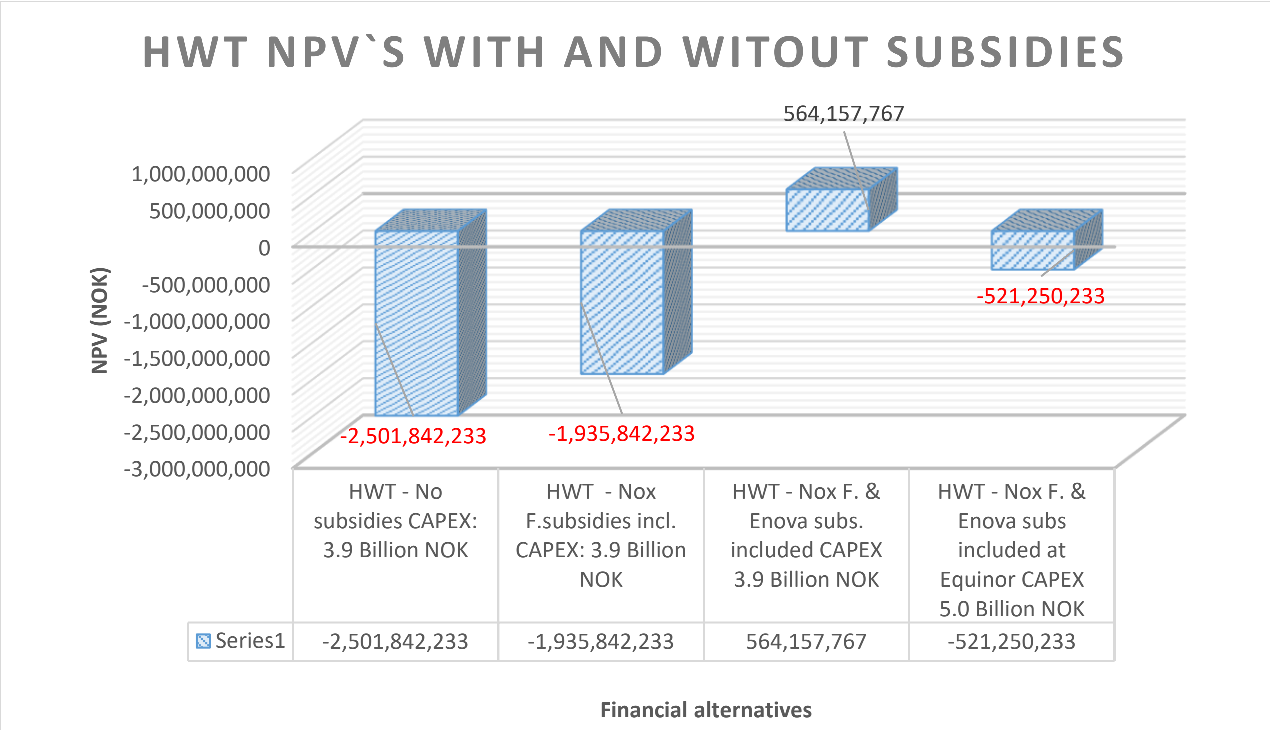


Figure XX: HWT with and without subsidies

HWT abatement costs are calculated with a CAPEX of both 3.9 billion NOK and 5 billion NOK, shown in the figure below and represented by blue bars. These are calculated with a 5 % discount rate. The EU ETS price used is the average of November 2018, the EUR/NOK exchange rate as well. This results in a quota price right beneath 200 NOK/ton. This quota price may increase a great deal in the future for reasons explained in section 1.5, but at the present time the cheapest estimate for HWT is still 10 times the price of a quota. The abatement cost tells us that this is a very expensive investment.

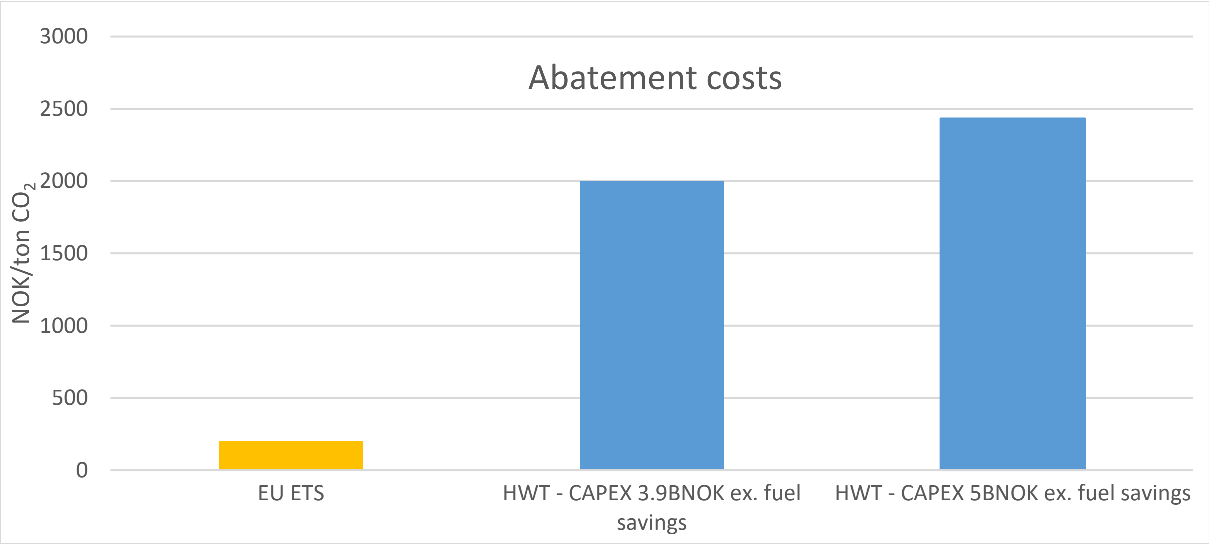


Figure 44: HWT abatement costs compared with explored CO_2-reducing projects in Klimakur 2020. r=5 %.

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Appendices

A: Frequency of wind speeds sorted in to bins from 1- 25 m/s

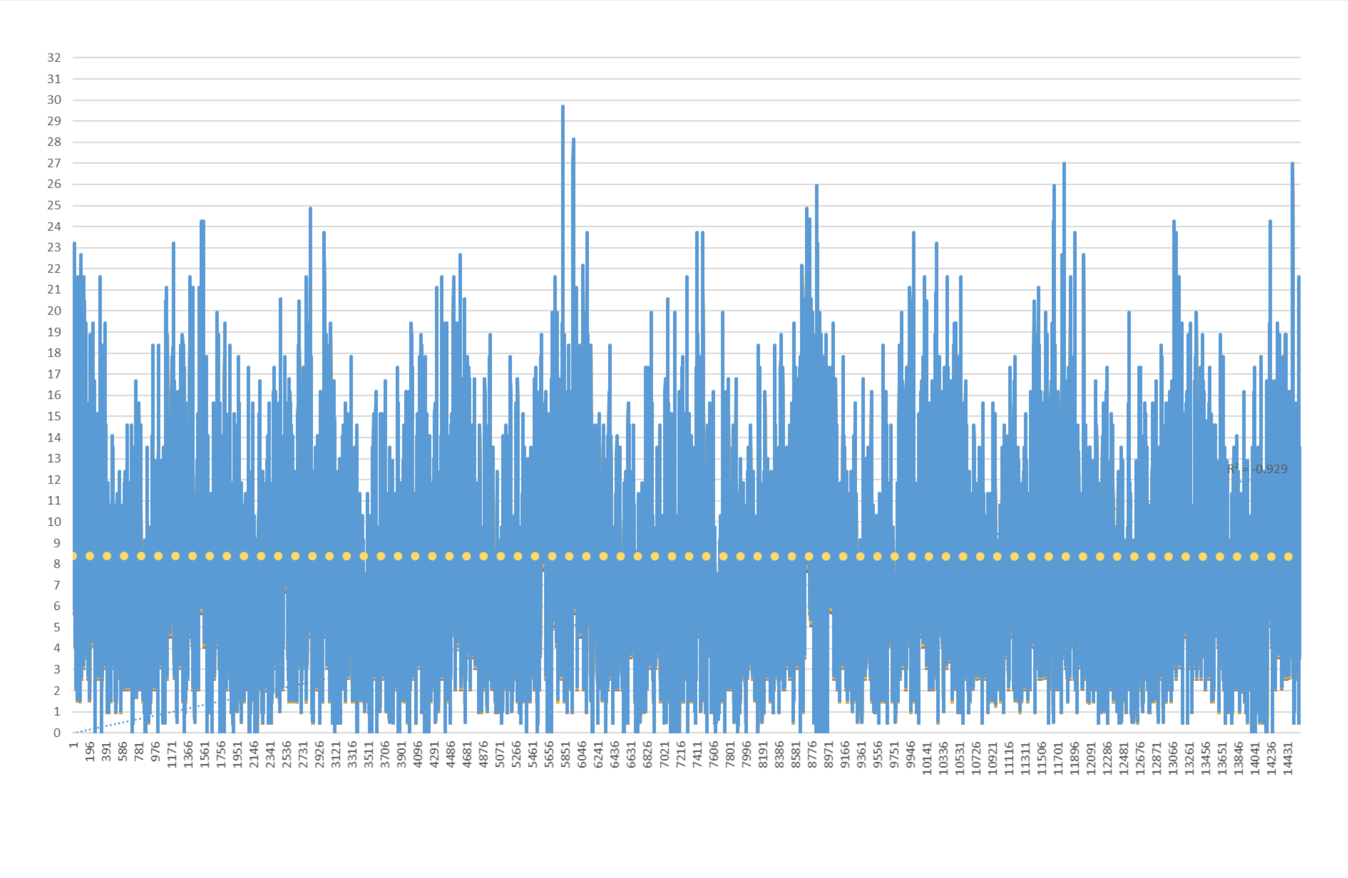
Bin	Altitude [m]					
	80	90	100	110	120	Weibull
1	336	336	336	336	336	0.031448
2	900	900	900	900	900	0.053097
3	1107	1107	1104	1104	1104	0.069184
4	1233	1233	1235	1235	1234	0.080101
5	1345	1345	1343	1343	1344	0.086179
6	1323	1323	1318	1317	656	0.087921
7	1341	1340	1347	1348	1379	0.086
8	1376	1377	1377	742	1371	0.081196
9	1182	1182	581	1215	1216	0.074323
10	1040	1040	1165	1165	1165	0.066163
11	830	830	901	901	901	0.057412
12	660	343	746	747	596	0.048645
13	526	585	585	583	472	0.0403
14	426	497	498	498	528	0.03268
15	228	347	348	350	426	0.025962
16	155	223	224	130	285	0.020222
17	140	140	139	166	167	0.015453
18	96	96	50	117	117	0.01159
19	58	57	82	82	82	0.008537
20	46	47	40	40	23	0.006178
21	16	16	39	39	46	0.004394
22	21	21	18	18	16	0.003072
23	10	7	16	15	21	0.002113
24	5	3	3	4	10	0.001429
25	4	6	6	5	5	0.000951

Bin 1 contains registered wind speeds between 1-2 m/s and so on.

B: Relative frequency of wind speeds sorted in to bins from 1- 25 m/s

Bin	Altitude [m]						Wind power density
	80	90	100	110	120	Weibull	
1	0.023327	0.023332	0.023332	0.023333	0.023333	0.031448	0.017611014
2	0.062483	0.062496	0.062496	0.0625	0.0625	0.053097	0.237875178
3	0.076854	0.07687	0.076661	0.076667	0.076667	0.069184	1.04606702
4	0.085601	0.085619	0.085758	0.085764	0.085694	0.080101	2.870817183
5	0.093377	0.093396	0.093257	0.093264	0.093333	0.086179	6.032509494
6	0.091849	0.091869	0.091521	0.091458	0.045556	0.087921	10.6349388
7	0.093099	0.093049	0.093535	0.093611	0.095764	0.086	16.5189154
8	0.095529	0.095618	0.095618	0.051528	0.095208	0.081196	23.28050844
9	0.082061	0.082078	0.040344	0.084375	0.084444	0.074323	30.34169919
10	0.072202	0.072217	0.080897	0.080903	0.080903	0.066163	37.05153587
11	0.057623	0.057635	0.062565	0.062569	0.062569	0.057412	42.79285885
12	0.045821	0.023818	0.051802	0.051875	0.041389	0.048645	47.07271325
13	0.036518	0.040622	0.040622	0.040486	0.032778	0.0403	49.58175305
14	0.029575	0.034511	0.034581	0.034583	0.036667	0.03268	50.21678361
15	0.015829	0.024096	0.024165	0.024306	0.029583	0.025962	49.06878725
16	0.010761	0.015485	0.015554	0.009028	0.019792	0.020222	46.38471706
17	0.00972	0.009722	0.009652	0.011528	0.011597	0.015453	42.51431426
18	0.006665	0.006666	0.003472	0.008125	0.008125	0.01159	37.8533217
19	0.004027	0.003958	0.005694	0.005694	0.005694	0.008537	32.79243128
20	0.003194	0.003264	0.002778	0.002778	0.001597	0.006178	27.67808471
21	0.001111	0.001111	0.002708	0.002708	0.003194	0.004394	22.78778891
22	0.001458	0.001458	0.00125	0.00125	0.001111	0.003072	18.31963197
23	0.000694	0.000486	0.001111	0.001042	0.001458	0.002113	14.39360627
24	0.000347	0.000208	0.000208	0.000278	0.000694	0.001429	11.06127176
25	0.000278	0.000417	0.000417	0.000347	0.000347	0.000951	8.320107282

C: Graphical representation of the frequency with yellow trendline and wind rose data:



	DD	345	15	45	75	105	135	165	195	225	255	285	315	Variable	Calm	Total	Rel.fr.	Cum.fr.
FF		14	44	74	104	134	164	194	224	254	284	314	344					
<=	1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0	0.3	1641	2.1	2.1
1.1	7	4.8	3.3	2.5	2.3	2	2.9	4.7	4.2	3.6	3.8	3.7	3.8	0		33224	41.6	43.7
7.1	13	4.4	3.9	1.4	0.8	1.1	3.5	8	5.7	4.6	3.6	2.7	3.3			34323	43	86.6
13.1	19	0.7	0.7	0.2	0	0.2	1.7	3.5	1.6	1	0.9	0.7	0.9			9616	12	98.7
19.1	25	0.1	0			0	0.3	0.4	0.1	0.1	0.1	0.1	0.1			992	1.2	99.9
>	25	0					0	0	0	0	0	0	0			65	0.1	100
Total		8093	6515	3384	2636	2765	6724	13358	9387	7582	6811	5795	6561	17	233	79861		
Rel.fr.		10.1	8.2	4.2	3.3	3.5	8.4	16.7	11.8	9.5	8.5	7.3	8.2	0	0.3		100	
Cum.fr.		10.1	18.3	22.5	25.8	29.3	37.7	54.4	66.2	75.7	84.2	91.5	99.7	99.7	100			
Mean	FF	7.4	7.9	6.3	5.2	6.2	9.4	9.9	8.7	8.3	7.9	7.3	7.8	1	0			
St.dev.	FF	3.8	3.8	3.4	3	3.8	5	4.6	4.2	4	4.1	4	4.1	0.6	0			