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Energy System for LNG Plant Based on Imported Power

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Problem Description

The following questions should be considered in the work:

a) An update of the need for electric and thermal energy in Snøhvit Train II as function of the selected Train capacity. The train capacity shall be selected in dialogue with StatoilHydro. The tool for doing the power and heat balance shall be scaling of Train I figures together with flow sheeting calculations of selected parts of the plant.

b) A discussion of the fraction of the power need in Snøhvit Train II that on an annual basis should be covered by new renewable energy production.

c) Selection of suitable new wind mill projects to cover the needed fraction of energy. Execute production estimates for the selected wind power farms.

d) Design of necessary grid infrastructure in order to provide Snøhvit Train II with renewable energy.

e) Consideration of achievable regularity of electric power import to a Train II. Also comment on the possibility of supplying (part of) Train I with imported power and the use of the existing LM6000 gas turbines as backup to wind power for both Train I and II.

f) Execute an investment analysis for the energy system to Train II in cooperation with StatoilHydro.

Assignment given: 19. January 2009
Supervisor: Geir Asle Owren, EPT

PREFACE

This report is the result of our work at the Norwegian University of Science and Technology during spring 2009. The thesis completes the final year of the Masters program in Energy and Environmental Engineering. It has been carried out at the Department of Energy and Process Engineering, Faculty of Engineering Science & Technology. The task description originated from the Snøhvit project environment in StatoilHydro and was thereafter formed in collaboration with us to fit common interests.

We feel that being two students responsible for the completion of this project has enhanced both the quality of the work process and the resulting report. It gave life to evaluation and constructive feedback along the way, which made us less dependent on guidance and supervision from others. Not being dependent on others still allowed us to seek external advice and expert help whenever this could contribute to improving the project work.

We met a very accommodating attitude throughout the Snøhvit organization, and other than Mr. Geir A. Owren, our supervisor, also Mr. Svein Nordhasli and Mr. Rune Jensen from the Snøhvit organization and Mr. Øyvind Bergvoll from StatoilHydro New Energy welcomed all types of questions. We also want to thank Mr. Tor-Erling Sandvik from StatoilHydro for welcoming us at Rotvoll.

Trondheim, June 2009.

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SUMMARY

It has been proposed to supply heat and power to Snøhvit Train II (STII) from onsite heat generation based on natural gas and power import from the power grid. Without carbon capture and storage, greenhouse gas (GHG) emissions from the combustion of natural gas in furnaces make a considerable contribution to the global warming potential (GWP) of this energy system. Depending on the interpretation of marginal power consumption, the power import also contributes to and increases this system's GWP. A recent SINTEF report claimed that European CO_2 emissions are reduced with additional renewable power production in Norway, and it has been suggested to invest in wind power in order to completely offset the GWP of the STII energy system.

This paper provides investment analyses for the proposed energy system. A scenario approach was used, with six different scenarios covering two dimensions. The first dimension is the origin of the grid power, with three different interpretations of marginal power representing Cases A, B and C. The other dimension is the STII train size, with two different sizes being analyzed, namely 50 % and 70 % of the Snøhvit Train I design capacity.

The proposed energy system was also analyzed with respect to security of supply. Improved reliability and transmission capacity, together with a stable, positive power balance, make a good foundation for security of power supply.

The power demand of the two train sizes was estimated to 101 MW and 141 MW, with corresponding heat demand of 94 MW and 131 MW. These estimates were based on a combination of HYSYS simulations and data provided by StatoilHydro (SH), and provided input for both the GWP analysis and the investment analysis. The GWP impact of each scenario determined the share of power import from the grid that would have to be replaced by energy harnessed from wind. The applied capacity factor was 39.6 %, and the rated wind power requirement for the six different scenarios ranged from 101 MW for the A.50 scenario to 257 MW for the C.70 scenario.

The break even (BE) energy prices were calculated for each of the six scenarios analyzed. If the power consumption is based solely on power import, with zero StatoilHydro (SH) share of grid reinforcements and no SH development of wind power, the BE power price would be 466 NOK/MWh. The inclusion of wind power development as part of the investment will increase the BE power price by up to 33 NOK/MWh. The additional SH share of grid reinforcement will add 86 NOK/MWh for the 50 % STII or 62 NOK/MWh for the 70 % STII.

It was shown that the investment in wind power to offset the GWP of the energy system might also be a reasonable way of hedging against increases in the market price of electricity. It was found that the share of STII power demand that is provided by wind power is one of the parameters that have the least influence on the project's net present value (NPV). A high share of wind power is an inexpensive investment in improving reputation and predictability of energy price.

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ABBREVIATIONS

BE price	Break Even price
CAPEX	Capital expenditures
CCS	Carbon Capture and Storage
CF	Capacity Factor, wind energy
CHP	Combined Heat and Power plant
CEOS	Cubic equation of state
Ecoinvent	Swiss database for environmental impacts, used with SimaPro
EOS	Equation of state
GHG	Greenhouse gas
GWP	Global Warming Potential
GWP100	GWP100 is measured in CO_2 equivalents and measures the GWP over a time span of 100 years, as defined by IPCC
HHC	Heavy hydrocarbon
HTF	Heat Transfer Fluid, heating agent
HYSYS	Process simulation tool
ILE	The amount of energy that would have been delivered to the end user if the power supply was not interrupted
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LPG	Liquefied Petroleum Gas
LNG	Liquefied Natural Gas
MEG	Mono Ethylene Glycol
MNOK	Million Norwegian Kroner
MUSD	Million US Dollars
Negawatt (NW)	The potential for reduction in energy demand
NGL	Natural Gas Liquids
NORDEL	Organization for the Nordic transmission system operators
NPC	Net Present Cost
NPD	the Norwegian Petroleum Directorate
NPV	Net Present Value
NVE	Norwegian Water Resources and Energy Directorate
OPEX	Operational expenditures
p.a.	per annum
PR	Peng-Robinson
RIVA	Risk and Vulnerability Analysis
SH	StatoilHydro
SimaPro	LCA Software by PRé Consultants
SRK	Soave Redlich-Kwong
STII	Snøhvit Train II
Train I	Snøhvit Train I
TSO	Transmission System Operator

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CHAPTER 1: INTRODUCTION

In its fourth assessment report, *Climate Change 2007,* the Intergovernmental Panel on Climate Change (IPCC) emphasizes not only the importance of mitigating climate change, but also the immediate urgency of dealing with this complex issue. Due to the polluting nature of fossil fuels the oil and gas industry often finds itself in the centre of attention in questions dealing with climate change. However, until new renewable energy is available at a competitive cost the world will continue to be dependent on fossil fuels. One of the most urgent measures to take is therefore to make the industry commit to reduce the CO_2 footprint of their products.

There are several compelling reasons why the oil and gas industry should be willing to take on these commitments. First, companies in the oil and gas sector will probably face stricter governmental regulations in near future as governments take steps to reduce greenhouse gas emissions through national policies. Tools like CO_2 taxes and carbon allowance trading are already in place in many countries. The Norwegian government has recently announced a goal of reducing the global CO_2 emissions corresponding to 30 % of Norway's emissions in 1990 by 2020, and two thirds of the reduction should find place domestically. Furthermore, they also have a goal of being climate neutral by 2030 (St.meld. nr. 15 2008-2009). To comply with policies based on these goals, especially those related to domestic reduction, oil and gas companies will have to implement measures reducing the carbon footprint of their production in Norway. Second, developing new technology and solutions to reduce greenhouse gas emissions can contribute to a competitive advantage, ensuring long-term profits for the company. Identifying risks and cost-effective reduction opportunities in the value chain can also enhance their competitiveness. Third, the industry should strive to meet the rising expectations from the general public and other external stakeholders, constantly more aware of the challenges related to climate change. Companies can gain a more positive reputation by taking proactive actions towards reducing the CO_2 footprint of their products and being transparent about their efforts. These actions can in turn give them the necessary goodwill and expertise for doing even more business in the future (WBCSD, no date).

StatoilHydro is one of many oil and gas companies that have to adapt to these changing times. To the benefit of the environment, and the benefit of the company, this report will look at the possibilities of reducing the carbon footprint of StatoilHydro's LNG production at Melkøya, Norway.

1.1 Objective

This paper has four main objectives. The first objective is to quantify the Snøhvit Train II (STII) heat and power demand as a function of the processing and liquefaction capacity. The second objective is to propose and describe an energy system to meet the heat and power demand imposed by STII. The third objective is to identify the global warming potential (GWP) of the proposed energy system and to propose measures to decrease the GWP to an acceptable level. The fourth objective is to perform an investment analysis and to identify the most vulnerable parameters of the proposed energy system.

1.2 Scope

This paper has the following scopes:

- The energy demand for STII should be estimated as a function of the LNG production capacity. It is assumed that STII is based on similar processes as Train I. The heat and power requirements for the Mixed Fluid Cascade (MFC) process and the fractionation will be estimated using HYSYS; a process simulation tool frequently employed by the industry. The remaining processes will be estimated based on empirical data.
- Potential bottlenecks in the national grid can prevent the grid from meeting the requirements imposed by STII. These bottlenecks must be identified and measures should be suggested to overcome these bottlenecks.
- Because regular power supply is of utmost importance for a gas processing plant, the expected regularity of the grid supply must be identified and discussed.
- The GWP of the STII energy system will be calculated for different scenarios. The scenarios will take into account the origin of the grid power and the size of STII. A GWP threshold level will also be suggested.
- Wind power is suggested introduced as a part of the STII energy system to reduce the GWP. First, the appropriate share of wind power in the energy system must be quantified for each scenario. Second, the rated wind power must be calculated for each scenario. Last, a rough screening of known wind farming projects in the vicinity of STII will be performed in order to find the projects most suitable to be part of the STII energy system.
- The investment analysis will be performed by use of an investment model developed in Microsoft Excel. The model will be made as realistic as possible and should take into account tax effects based on publicly available information from the Norwegian government. The investment analysis should also include a realistic estimate of the most important expenses and the time value of money. Additionally, the investment analysis should include a sensitivity analysis that identifies the most vulnerable parameters in the STII energy system.

1.3 Limitations

The limitations of this paper are mainly due to the following.

Determination of energy figures based partly on work of others

Uncertainty lies in using numbers for which the underlying assumptions are not fully known. Energy figures based solely on own simulations would be preferable. However, due to the time available, it was decided with advice from the supervisor that trying to simulate the full LNG process would be unwise, and company provided data were combined with simulation results to yield STII energy estimates.

HYSYS work subject to time pressure

First, time had to be spent on getting familiar with the HYSYS software and its way of working, as this had not before been used by the authors. Second, results were needed early, as they make input to the GWP and investment analyses. Performing the simulations as stand-alone work would have allowed an optimization of the energy demand with respect to the most relevant degrees of freedom, and it would have allowed more effort to be put in estimating the heat demand of distillation columns. The latter would give the STII energy estimates a stronger foundation in own simulations.

Simplified production estimate for wind farming

Wind speed increase with height because of the surface shear, and a scaling of wind data from 10 meters height was necessary due to lack of data from hub height. This scaling enhances the effect of terrain induced local acceleration on wind data, an effect that is likely to be relevant for the measurement stations used, since they are not situated in flat terrain. Furthermore, advanced wind analysis software would have contributed with better production estimates. The appliance of such would have been well beyond the scope of this work, but the lack thereof still represents a limitation in the work performed.

Possible simplifications in the investment model

The investment model was developed in Microsoft Excel with basis in publicly available information from the Norwegian government. Few numerical examples were provided along with this information so the potential for misinterpretation exists. In addition, the fiscal framework covered in this paper is rather complex and goes beyond the understanding obtained through classes attended by the authors of this report. A significant amount of time has therefore been invested in gaining a better understanding of the fiscal framework.

The complexity of the assignment

This work covers many topics of a complex energy system, many which could be the basis of stand-alone papers. More in-depth treatment of the different topics could have been carried out if fewer topics were in focus, or if more manpower were available. For recommendations on future work, confer with chapter 5.

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CHAPTER 2: BACKGROUND

This chapter provides background information about the Snøhvit LNG project and explains the expansion plans for the Snøhvit LNG project located on Melkøya. Section 2.1 is based on public information from StatoilHydro (SH) and provides an overview for readers unfamiliar with the Snøhvit LNG project. In section 2.2, plans for erecting a second LNG train – STII will be discussed. Finally, section 2.3 explains the fundamental parts of the energy system proposed and analyzed in this paper.

2.1 Snøhvit LNG Train I

2.1.1 The Snøhvit Reservoirs

Snøhvit LNG is the first offshore development of any oil or gas reservoir in the Barents Sea and started its operation in 2007. The three gas reservoirs Snøhvit, Askeladd and Albatross are located offshore of Finnmark, the northernmost county of mainland Norway. All installations offshore are placed at the seabed at depths of 250-345 meters. In total, 193 billion standard cubic meters (bcm) of natural gas is recoverable from the three reservoirs. Additionally, 113 million barrels of condensate and 5.1 million tons of natural gas liquids (NGL) are recoverable. The operator of Snøhvit LNG is SH.

2.1.2 Melkøya and Snøhvit Train I

The well stream from the three reservoirs is piped 143 km to an onshore facility at Melkøya, where all processing and energy production takes place. After processing, the natural gas is cooled down and converted to LNG – liquefied natural gas. The LNG is then stored in large tanks before it is shipped by specially designed LNG carriers. Figure 2.1 shows the processing plant at Melkøya and one of the LNG carriers. These carriers transport the LNG to markets in Southern Europe and North America. The most important receiving terminal for SH is the Cove Point terminal nearby Washington DC, USA. A total production of 4.3 million tons of LNG is shipped from Melkøya annually. Snøhvit is the first exporting LNG facility in Europe.

Figure 2.1: The processing plant at Melkøya. Image courtesy of StatoilHydro

The energy required at Melkøya is produced on site in a combined heat and power (CHP) plant fired with locally refined natural gas. Hot oil is used as a heating agent. Even though the process on Melkøya is among the most energy efficient LNG liquefaction processes in the world, the CHP plant has annual CO_2 emissions of approximately 900,000 tons. This corresponds to about 2 % of Norway's total CO_2 emissions.

2.2 Expansion of LNG Production Capacity

2.2.1 Snøhvit Train II (STII)

Increased global demand for LNG has made SH investigate the possibility of erecting a second LNG train at Melkøya – STII. The idea behind building a second LNG train is that this will increase the value of the natural gas by extracting it earlier in time. An expansion of the processing and liquefaction capacity, and thereby an increased power and heat demand, would historically entail the construction of an additional CHP plant.

As discussed in the introduction the Norwegian government aims to curb the domestic CO_2 emissions significantly, among others by implementation of carbon capture and storage (CCS) on natural gas fired energy plants (St.meld no. 15 2008-2009). CCS is currently an expensive and immature technology involving considerable technological risk for SH. In addition to the risk, the energy efficiency of the LNG production decreases substantially when CCS is implemented due to significant energy requirements by the CO_2 treatment plant itself. To sum up, a CHP plant with CCS has disadvantages with regard to maturity, reliability and energy efficiency. This paper will evaluate an energy system based on power import through the grid, and heat from gas furnaces without CCS.

2.2.2 Two Relevant Train Sizes: 50 and 70 % STII

The train size will be selected with basis in available gas resources, economic analyses and the feasibility of the energy system. SH has done a preliminary screening and recommended the use of two different train sizes as a basis for this analysis; 50 and 70 % STII. The percentage is related to the design LNG production capacity of Snøhvit Train I which is 4.3 million tons per year. With the commissioning of STII, LNG deliveries from Melkøya will total 6.5 or 7.3 million tons annually, depending on the choice of train size.

2.2.3 Project Schedule for STII

The start-up of STII is forecasted to the beginning of 2016. Before start-up, however, SH must expect several years of detail engineering, regulatory work for obtaining the proper governmental permits and finally the actual construction works. The technological and economic lifetime of STII is expected to be 25 years.

2.3 Proposed Energy System for STII

This paper will evaluate an energy system based on power import through the grid and heat from gas furnaces without CCS, instead of a CHP plant with CCS. An illustration of the proposed energy system can be seen in figure 2.2. Fuel gas flows from the STII process plant to the gas furnace as illustrated with the green arrow, while heat flows in the opposite direction as illustrated with the red arrow. Power is supplied through the grid, using one of three assumptions regarding the origin of the power, as shown by the blue arrows. Other material flows in the figure are illustrated with black arrows, i.e. emissions of NO_x and CO_2 to the atmosphere, crude gas and liquefied natural gas (LNG).

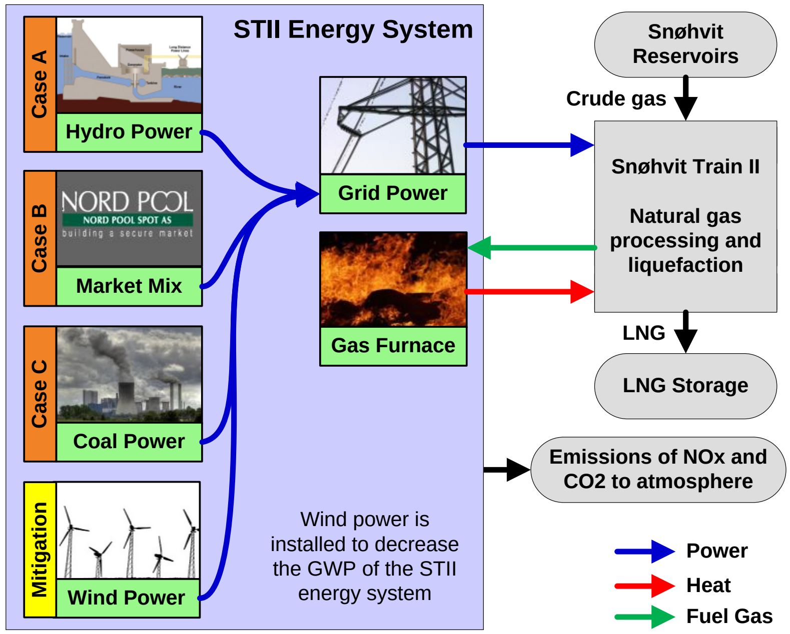


Figure 2.2: Block diagram of the proposed energy system for STII

The different assumptions for the origin of power are in the following referred to as case A, B and C. These three cases will be described in more detail in section 2.3.1.

Wind power is introduced to the grid in order to offset the CO_2 emissions caused by the STII energy system. The rated wind power to be installed depends on several factors, e.g. the local wind conditions, the origin of the imported grid power and the STII power demand.

2.3.1 Power Import from the Grid

In the proposed energy system, all power that is required by STII will be supplied through a connection to the national power grid. Today, only a weak connection exists, with the capability of supplying 50 MW. This is about the rated power of one LM6000 gas turbine, and the line thus functions as spare capacity in case of gas turbine trips. Even though the power in the proposed energy system is supplied through the grid it is still important to be aware of the origin of the consumed power. This is necessary in order to determine the global warming potential (GWP) of the STII energy system. The GWP is measured in CO_2 equivalents and takes into account the impacts from all compounds emitted over the lifecycle of an energy source.

Forecasted power take-offs from the grid, like the one proposed for STII, is often characterized as marginal power consumption as it is on the margin of what is already consumed. The origin of marginal power consumption is often disputed, and table 2.1 provides three applicable viewpoints on the origin of the power consumption of STII: hydro power, market mix and coal power. The viewpoints are labeled as Case A, B and C for future reference. Note that more viewpoints exist; however, these cases are found representative to cover the range of viewpoints relevant to calculate the GWP.

Case	Description	
A	Hydro power:	Norway mainly generates hydro power. According to NVE, more than 98 % of the Norwegian power generation was hydro power in 2007. The marginal power consumption should therefore be considered as hydro power.
B	Market mix:	Norway is part of an international market place for power trade (Nord Pool). The marginal power consumption should therefore be considered as a market mix, where the national production and the average effects of import and export of power with Denmark, Sweden, Finland and Russia is taken into account.
C	Hard coal:	STII's power consumption comes in addition to the current power balance, and the marginal power consumption should therefore be considered as imported coal power from otherwise idle coal power plants.

Table 2.1: Viewpoints on the marginal power consumption of STII

2.3.2 Onsite Heat Generation from Gas Furnaces

Heat generation required by STII happens in onsite gas furnaces without carbon capture and storage (CCS). Heat is transferred to a heating agent, which delivers heat to the entire process plant. Heat supply by use of gas furnaces is considered a mature technology. Expenses and emissions of exhaust gases are therefore predictable with a high level of certainty.

As there is no carbon capture, heat supply will contribute significantly to the total GWP of the STII energy system. It was desirable to offset this GWP. The proposed way of achieving this was to develop renewable energy production in the region, in form of wind farms. This measure was considered superior to implementation of CCS, both with respect to maturity and energy efficiency. CCS is seen as an expensive technology which involves considerable technological risk due to its immaturity.

Section 2.3.3 discusses further how the GWP of the STII energy solution can be offset by wind power.

2.3.3 GWP Offset by Wind Power

This paper suggests development of wind farms to offset the GWP for the STII energy solution. Modern wind farms utilize the wind resources in the region to produce power with a very low GWP. The rated wind power to be installed depends on several factors, e.g. the local wind conditions, the origin of the imported grid power and the STII power demand. Due to the natural fluctuation in power production from wind farms the estimation will be based on the average annual power production. It is assumed that redundant power production in periods of strong wind is sold to the spot market, while power is bought from the spot market in periods with low winds. The methodology for quantifying the rated wind power is described in section 3.4, while the results can be found section 4.4.

2.3.4 Six Different Scenarios

The investment analysis will be based on six different scenarios covering two dimensions. The first dimension is the origin of the grid power. Three different sets of assumptions are classified as Case A, B and C as discussed in section 2.3.1. The share of wind power in the energy system will be different for each of the three cases. The other dimension of the scenarios is the STII train size. Two different train sizes will be investigated; 50 % and 70 % STII of the full LNG production capacity of Snøhvit Train I.

Combining the two dimensions, investment analyses will be performed for a total of six different scenarios. The scenarios are named with a logical system; for example, Case B and train size 70 % will be referred to as scenario B.70. The six different scenarios are illustrated in figure 2.3.

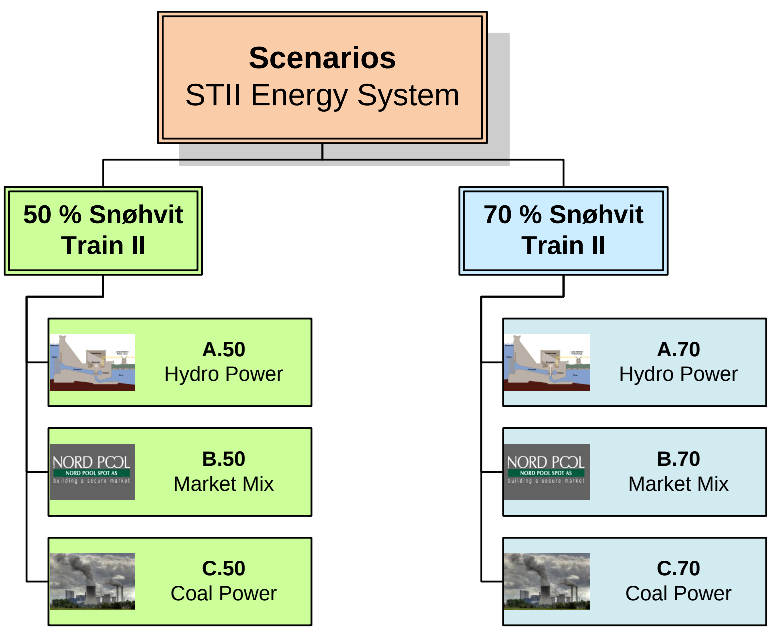


Figure 2.3: Scenarios for the STII energy system

CHAPTER 3: METHODOLOGY

3.1 Heat and Power Requirements for STII

Section 3.1.1 provides an overview of the LNG process of the existing rain I. The same process was assumed to be the baseline STII. The next section describes how the energy figures for STII was to be estimated partly on basis of the Train I figures and partly with basis in process simulations performed in this work. Sections 3.1.3-4 explains important features about the set up of a HYSYS simulation.

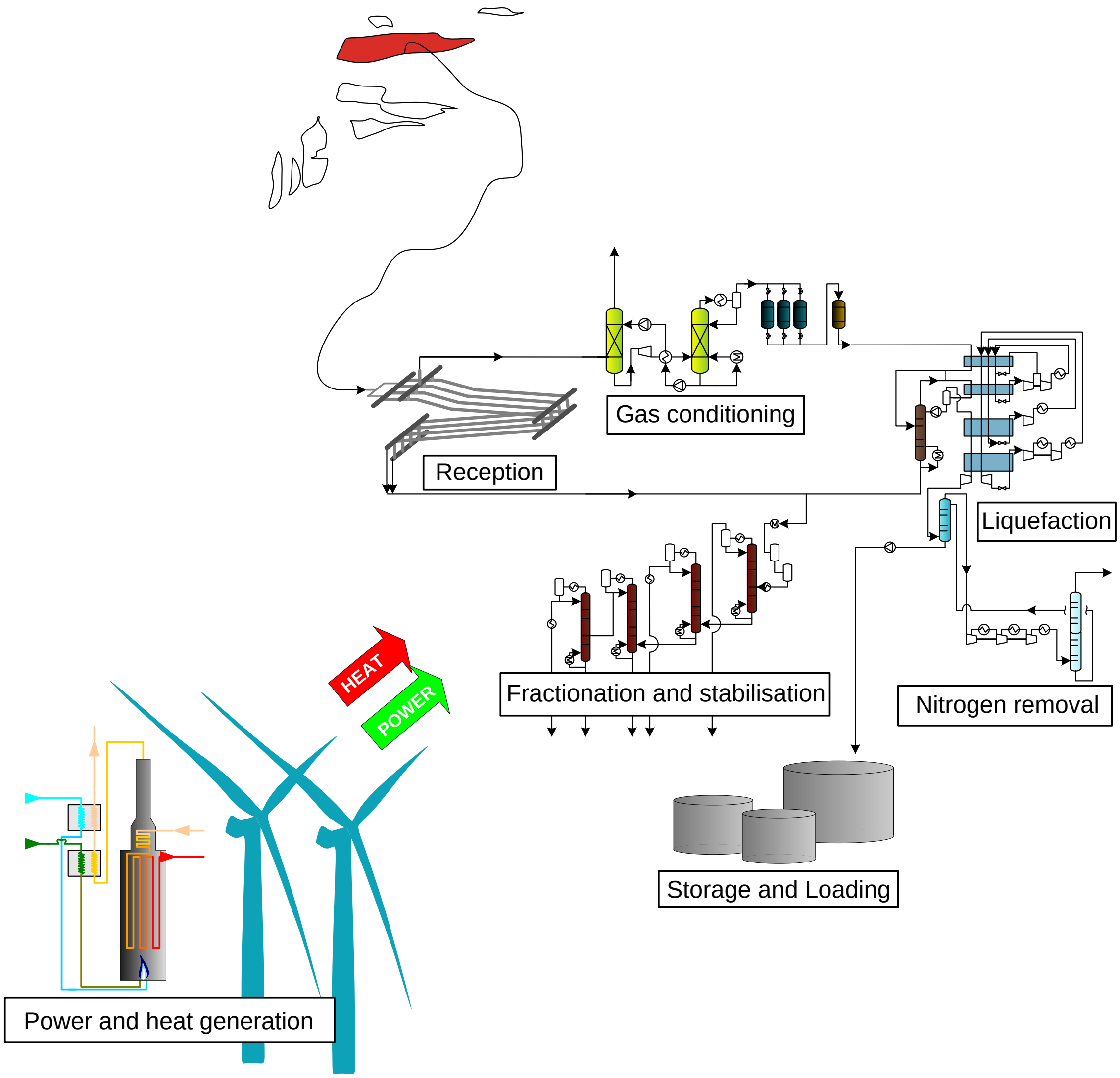


Figure 3.1: Snøhvit LNG value chain, by subsystem

3.1.1 General Process Overview

The value chain from pipeline to LNG ship was split up and organized in seven subsystems, see figure 3.1. Each subsystem comprises one or more services delivered to the LNG production process. The seven subsystems altogether comprise all main parts of the LNG production process. The division of the Snøhvit LNG process into subsystems made a systematic approach to identify which processes that were the largest consumers, and which power and heat consumers that were directly linked to the choice of energy system.

Reception

The most important services delivered by the reception subsystem are:

- Services delivered by the slug catcher
- MEG recovery and re-injection
- Future pre-compression of feed gas

When the piped gas reaches shore, it accumulates in the slug catcher. At Melkøya, the slug catcher in place for Train I holds enough capacity for a second train. The purpose of the slug catcher is tripartite. The most obvious purpose is that it catches slugs of liquid coming from the offshore pipeline, and thereby functions as a buffer before the processing plant to prevent damage. Furthermore, it ensures that the operating pressure is constant, by providing the processing plant with steady, not intermittent feed streams. Lastly, these feed streams are of different type; the slug catcher separates gas, condensate and MEG-rich water.

The MEG-rich water is treated in the MEG Recovery system and re-injected to be mixed with the multiphase flow coming from the gas field offshore. MEG inhibits gas hydrates to form in the pipelines.

In the future, when the reservoir pressure has lowered to an extent that makes the pressure of the natural gas stream insufficient for it to be treated in the processing plant, gas re-compression must be introduced. These compressors sort under the Reception-subsystem.

Gas conditioning

The main services comprised by the gas conditioning subsystem are:

- Removal, drying and re-compression of CO_2
- Removal of water
- Removal of mercury

In general, components that freeze out during gas liquefaction must be removed, along with poisonous and corrosive components. Additionally, sales gas specifications must be met. Freezing of water, CO_2 and heavier hydrocarbons (HHC) will plug the narrow channels in the plate-fin heat exchangers. The freezing temperature of HHC and CO_2 is strongly dependent on the amount present; hence the mole fraction of these components decides the lowest temperature in the LNG heat exchangers (Aspelund and Gundersen 2009).

Mercury must be removed because of its corrosiveness. CO_2 is also corrosive, but in addition it reduces the heating value of the LNG and it might freeze out during liquefaction. At Snøhvit, the sour gas CO_2 is removed by an amine based absorption process. Water and mercury are both removed from the natural gas stream in adsorption processes. Such processes are based on physical rather than chemical binding, and can give a very high component recovery rate. Molecular sieves are installed for the dehydration, whereas mercury removal happens in a mercury filter (Fredheim et al. 2007).

Often, the removal of HHC for purification and value enhancement happens upstream of the liquefaction plant and could therefore sort under the gas conditioning subsystem. However, at Snøhvit the HHC extraction is integrated in the liquefaction part of the plant and thus sorts under the Liquefaction subsystem.

Liquefaction

This part of the plant comprises two main services;

- Cooling of natural gas into its end state, LNG
- Extraction of HHCs

The liquefaction plant is based on technology patented by Statoil and Linde, namely the Statoil-Linde Mixed Fluid Cascade (MFC) process.

Natural gas liquids (NGLs) form during pre-cooling and must be separated from the natural gas stream in the HHC removal column. The content of HHC should be below 1000 ppmv (Pettersen 2008), and the extracted NGL is sent to fractionation and can be sold as LPG and condensate or used for refrigerant make-up.

When the natural gas has been cooled to its end state LNG, at high pressure, the pressure is reduced in an expander, close to its dew point but ensuring that two phase flow does not occur. Thereafter, it is throttled true a valve, to just above atmospheric pressure, before the vapor phase is stripped of in the nitrogen stripper.

Nitrogen removal

The nitrogen removal subsystem has one important task, namely:

- Remove nitrogen from the flash gas

The flash gas contains much nitrogen, but even more methane. These are the most volatile components of the LNG and vaporize first. The reason why nitrogen must be removed is split; LNG heating value requirements and storage and transport specifications must both be satisfied. Methane has both a significant GWP and a significant heating value, and should hence not be vented together with the nitrogen; it can rather be sold as LNG. Therefore, the flash gas at Snøhvit has to be treated before it can be vented to the atmosphere.

The Nitrogen Removal Unit (NRU) is based on cryogenic distillation. First, the flash gas must be cooled, to make the distillation of methane and nitrogen possible. Power is needed to provide the cooling. After the distillation, nitrogen gas is released to the atmosphere, while liquid methane is fed back to the nitrogen stripper.

Fractionation

This subsystem deals with condensate and HHCs in general. Lighter hydrocarbons are also involved, but are bi-products and are sent to other parts of the plant to mix with other streams for further processing. The main tasks of this subsystem are:

- Fractionate feed streams to yield stabilized sales products
- Provide the Liquefaction subsystem with refrigerant make-up

Storage and loading

In order to safely store and load the LNG, LPG and condensate, the following services must be delivered:

- Fill storage tanks
- Load ships
- Prevent rollover in the LNG tank by circulating the stored volume

Energy utilities

Energy demand related to the energy supply sorts under this label. For train I, this demand relates to:

- Operation of the CHP
- Tempered water

3.1.2 Estimating the Energy Requirements of STII

Combine data sets

The energy figures for STII was estimated partly on basis of Train I figures and partly with basis in process simulations performed in this work.

Data set I: Train I energy figures

Train I energy figures were provided by SH in connection with the project thesis preceding this master thesis (Bomstad and Nordland 2008). In fall 2008, these numbers were assumed to be credible; however, some inconsistency was involved. The information provided by the company for the project thesis has been combined with additional data made available in spring 2009 to yield better Train I energy figures.

Power figures for Train I were available only in form of over-complex lists, giving the operational mode and rated power of components. The energy demand of Train I was found by assuming that components in continuous operation were always running on rated power load, and that intermittently operated components were running at their respective rated power 40 % of the time. The subsystems described in section 3.1.1 made a useful basis for grouping and organizing the data, and made easier the identification of power demand per service provided to the LNG process.

Heat figures were available per service for the largest heat consumers. The total heat figure was adopted from the project thesis from fall 2008 (Bomstad and Nordland 2008).

Data set II: Process simulations

The available power figures for Train I were based on rated power rather than actual power load, as described in the former paragraph. It was therefore a goal to simulate consumers that make up the major part of the total energy demand of Train I, to compare and see if the Train I figures were credible. Simulation results do not include margins such as those included in Train I rated power with the purpose of covering peak load and taking ageing, contingency and losses into account, and thereby represents actual (design) power consumption.

It was known beforehand that the Liquefaction subsystem is the greatest power consumer, and this was therefore chosen for simulation. Heat demand, on the other hand, is largely related to boiler duty in columns. Simulation of distillation columns can be very comprehensive, and with advice from the supervisor it was decided that this should not be the main focus. Moreover with advice from the supervisor it was decided that a simulation of the entire processing plant would be a too comprehensive task.

The Liquefaction subsystem for STII was assumed not to differ from Train I. This means that the liquefaction plant is based on the Statoil-Linde MFC process, with integrated HHC removal. A process diagram of the MFC process is shown in figure 3.2. The HHC removal is not shown in this figure but takes place between heat exchanger E1A and E1B in the pre-cooling section. The processes were simulated in HYSYS.

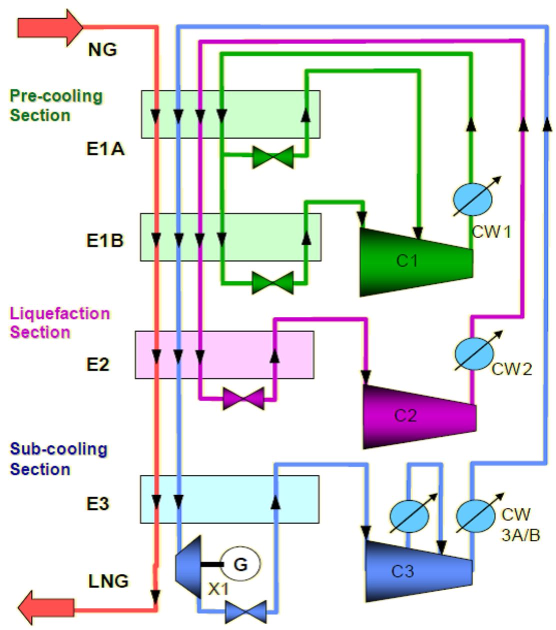


Figure 3.2: Process diagram of the Statoil-Linde Mixed MFC process (Pettersen 2008)

Identify energy saving potential

If parts of the power and heat demand of Train I were not relevant to the energy system of STII or could be reduced by changing the process, these savings should be subtracted from the Train I figures before using them to estimate the energy requirements of STII. Such saving potential therefore had to be identified. Large consumers that could be optimized, or consumers for which the process figuration could be changed to yield a different energy demand, were therefore mapped.

The largest consumers represent the largest potential for reduction in energy demand, i.e. negawatts (NW). The mapping of the main heat and power consumers in Snøhvit Train I on a per service basis made the starting point for an evaluation of whether the largest consumers can consume less energy. This could for example be achieved by choosing more energy efficient processes. Small changes to the existing design might also reduce the energy need.

Process simulations

This section provides a description of the simulated processes.

The MFC process cools natural gas by use of three mixed refrigerant cycles. The cooling circuits of the MFC process all use mixed refrigerants. This enables cooling of natural gas to happen at gliding refrigerant temperatures. This lowers the temperature difference between the natural gas and the cold refrigerants during heat exchange, and is particularly important at low temperatures. At low temperatures, the extra power input needed per heat transfer across a certain temperature difference, increases more than exponentially as temperature is reduced (Pettersen 2008). The efficiency of the cooling is thus determined partly by the composition of the refrigerant streams. As depicted in figure 3.3, the phase envelope for a mixture of methane and ethane can be anywhere within the vapor pressure curves of the pure components. The composition of refrigerants is thus an important degree of freedom in the design of a liquefaction plant.

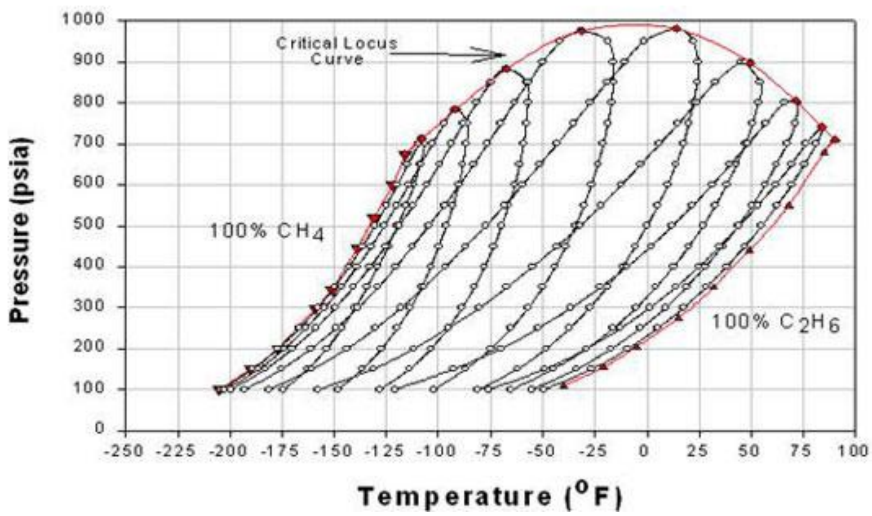


Figure 3.3: Effect of composition on phase behavior (Bloomer et al. 1953)

The higher the pressure at which the natural gas stream is cooled, the lower the power demand for the cooling cycle compressors will be. This is because the condensing temperature of the natural gas stream rises with increasing pressure, so that less cooling must be provided, see figure 3.4.

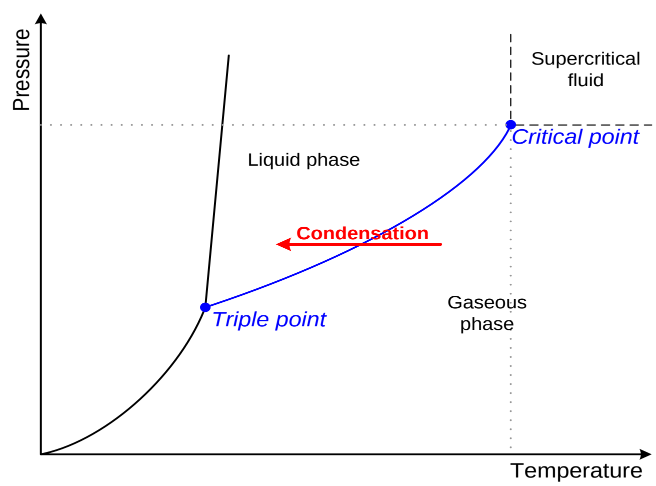


Figure 3.4: Pressure-Temperature diagram with vapor pressure curve

However, the pressure level is limited by the integrated HHC removal. The distillation column cannot operate at too high pressures; it must be lower than the critical pressure of the overhead product stream. Difficulties occur near the critical point, which is where the phase boundary between liquid and gas terminates, i.e. at the high temperature extreme of the liquid-gas phase boundary in a p-T-diagram, see figure 3.4. The gas-liquid co-existence curve is a plot of vapor pressure versus temperature. As pressure rises, the liquid phase is subject to thermal expansion and becomes less dense while the gas phase becomes denser. At the critical point, the curve ends because after this there is no distinction between the two phases, i.e. no co-existence of gas and liquid. The fluid is said to be supercritical. It is homogenous and separation cannot be achieved.

It was not straightforward to specify the column so that calculations converged. Several approaches were used and are not reproduced in this paper. Relevant literature is Smith (2005).

Simulations were done for both train sizes, i.e. 50 and 70 % STII, by adjusting all refrigerant streams by the same factor as the natural gas feed stream. For an STII size of 70 %, mass flows of refrigerant were also cut to 70 %, and so on. The logic of adjusting flow rates in this manner follows from a simple energy rate balance, see appendix A.

Assumptions

Assumptions are tabulated and summarized in appendix A.

The ambient temperature at Melkøya varies over the year, and the energy demand for the LNG plant will thus be subject to fluctuations. It has been assumed that hot process flows are cooled against sea water at a design temperature of 6^{o}C. The seasonal swing in heat and power demand and production was not looked into.

For heat exchangers cooling gaseous process flows against sea water, a minimum approach of 10^{o}C has been assumed. Exchangers that cool liquid process flows have been assumed to reach a minimum approach of 5^{o}C. Moreover it has been assumed that sea water cannot take up more heat than what increases its temperature by 8^{o}C. Refer to appendix A for assumed pressure drops experienced by the process flows.

In the MFC process, the cooling of NG to LNG is obtained with help of two different types of heat exchangers. Plate-fin exchangers are used for the pre-cooling circuit, whereas spiral wound heat exchangers (SWHE) are used for liquefying and sub-cooling the natural gas. The geometry of these two types of heat exchangers differs significantly. Hence, so do also the pressure drops experienced by the involved process flows. Refer to appendix A for the assumed values.

It was assumed that rotating equipment can be designed to operate at certain efficiencies, given the process flow rates and composition. In other words, the simulations were carried out without concerning for what kind of rotating equipment that is readily available from series production, and efficiencies have not been looked up in manufacturer brochures. For simplicity, all compressors and turbines have been assumed to have polytrophic efficiencies of 82 %, while pumps have been assumed to have adiabatic efficiencies of 85 %. For compression in several stages with inter-cooling and thereby pressure drop in the cooler, the intermediate pressure was found by assuming equal pressure ratio for each stage.

In the Snøhvit LNG process, mixed refrigerants consist of propane, ethane, methane and nitrogen. The pre-cooling refrigerant has the highest propane content, while nitrogen is only or mostly found in the sub-cooling refrigerant.

The intermediate temperatures of natural gas are closely connected with the composition of the refrigerants, and these temperatures are also reproduced in appendix A, along with the remaining input to HYSYS.

Estimate the STII energy demand

The Train I energy figures were combined with the process simulation results to estimate the STII heat and power demand, through equations 3.1 and 3.2. The Train I figures were assumed to scale linearly with train size. Contingency and losses were taken into account by adding a factor of 15 % on top of the output data from the simulations. Train I energy figures were assumed to have contingency and losses already factored in.

In the material provided by the company, ageing has been taken into account by assuming a linear profile for the first three years of operation, transitioning into a constant ageing effect of 2 % power increase throughout the plant lifetime. Rotating machinery will for example run on a lower efficiency after being exposed to wear. When estimating the STII power consumption, an ageing effect of 2 % has been added to the power consumption right from the start.

$$P_{STII}^{i} = \alpha \cdot \left[\zeta \cdot P_{HYSYS}^{i} + \frac{i}{100\%} \cdot \left(P_{TrainI} - \Delta P_{TrainI} - P_{Simulated.TrainI} \right) \right] \quad (3.1)$$

$$Q_{STII}^{i} = \frac{i}{100\%} \cdot \left(Q_{TrainI} - \Delta Q_{TrainI} \right) \quad (3.2)$$

where

i = $STII$ $percentage$ $size$ $relative$ to $train$ I $full$ LNG $production$ $capacity$ of $4.3\,mtpa$

α = $ageing$ $factor$

ζ = $contingency$ and $losses$ $factor$

P^i_{STII} , Q^i_{STII} = $estimated$ $power$ and $heat$ $demand$ for $STII$ of $size$ i

P^i_{HYSYS} = $HYSYS$ $power$ $figures$ for the $simulated$ $part$ of the $plant$, for $STII$ of $size$ i

P_{TrainI} , Q_{TrainI} = $power$ and $heat$ $figures$ for the $full$ $scale$ $train$ I

ΔP_{TrainI} , ΔQ_{TrainI} = $likely$ $reduction$ in $power$ and $heat$ $figures$ for $train$ I $when$ $adapting$ $them$ to $STII$

$P_{Simulated.TrainI}$ = $train$ I $figures$ for the $part$ of the $plant$ $that$ is $simulated$ in $HYSYS$

3.1.3 Adequate Flow Charts

Adequately detailed process flow diagrams were needed in order to:

- define different subsystems of the Snøhvit LNG process
- identify energy demand on a per component level
- evaluate how energy demand could be reduced by introducing changes to the existing process design
- model the parts of the LNG process that were selected for simulation

Process diagrams of a low, but for most purposes sufficient detail level, were available from lectures given in courses at NTNU (TEP4185, TEP10, TPG4140). More detailed charts were provided by StatoilHydro, but these were subject to secrecy, and were only used for the authors to gain a thorough understanding of how the processes work and are integrated.

The flow charts provided in this thesis are all based on material already available to public and are self made.

3.1.4 Process Simulation Tool: Hysys

Process simulations were carried out by using Aspen HYSYS software. From the home page of the software developer, HYSYS is described as follows (Aspentech):

“Aspen HYSYS is a market-leading process modeling tool for conceptual design, optimization, business planning, asset management, and performance monitoring for oil & gas production, gas processing, petroleum refining, and air separation industries.”

HYSYS is the simulation tool commonly used by StatoilHydro and was therefore the natural choice of software to be used in this master thesis.

Model definitions

In predicting the state of gases and liquids at high pressures and low temperatures the ideal gas law is no longer applicable. It becomes increasingly inaccurate and cannot predict the transition between phases. Several more complex models have been developed and are available in HYSYS. These can be used in order to describe the properties of a mixture of fluids under a range of conditions more accurately than the ideal gas law. Having an equation of state (EOS), virtually any property of a fluid can be derived. The question is which EOS is the most suited. A short description of relevant equations of state is given in the following paragraphs.

The accurate prediction of pure component vapor pressures is prerequisite for accurate vapor-liquid calculations, and is one of the important features of applying a cubic equation of state (CEOS). The first CEOS that represented both liquid and vapor phases was proposed by van der Waals in 1873. This was modified and considerably improved by Redlich and Kwong (1949).

The Redlich-Kwong (RK) CEOS was extensively used for engineering calculations for vapor phase properties of mixtures consisting of non-polar components, such as hydrocarbons. But still, it could not calculate vapor-liquid equilibrium accurately. This was, however, improved by Soave's modification to the RK CEOS model in 1972. Soave introduced a temperature dependent alpha function. In fact, this expression was adjusted to fit the vapor pressure data of hydrocarbons. Numerous other expressions have been proposed for the alpha function. In general, a CEOS can provide an accurate description of any component from the triple point to the critical point, by adjusting the alpha-coefficient. Soave's modification gained widespread popularity, and used together with the RK CEOS, it makes up what is known as the SRK CEOS (Soave 1972).

An alternative to the SRK CEOS model is the Peng-Robinson (PR) CEOS. The latter is based on an expression that is slightly different from the Redlich-Kwong equation in the volume function. The PR was proposed by Peng and Robinson in 1976. This too uses the expression for the alpha function developed by Soave. One of the goals behind the development of the Peng-Robinson equation was that it should be applicable to all calculations of fluid properties in natural gas processes. Moreover, it should provide reasonable accuracy near the critical point (Peng and Robinson 1976: 59–64).

Both the PR CEOS and the SRK CEOS are applicable for non-polar mixtures. Soave's expression has helped both the RK and the PR become widely used equations of state in industry, for correlating the vapor-liquid equilibrium of systems containing non-polar and slightly polar components. The difference between the two, SRK and PR, is that the latter improves the calculation of liquid density for mid-range hydrocarbons relative to the former. According to Twu et al (1994) the PR gives better liquid densities for hexane, but worse for methane.

The natural gas stream that comes from the slug catcher at the Hammerfest LNG plant consists mainly of hydrocarbons. Some water, MEG and CO_2 is also present, and are subject to removal. For mixtures containing polar components, special rules might have to be applied for the CEOS models to deliver accurate vapor-liquid calculations. As the gas stream that enters the liquefaction plant has gone through gas conditioning and can be considered a non-polar mixture, the SRK and PR CEOS should be applicable without such. Both models can be used for the HYSYS simulations, without modifications.

In choosing one model over the other, one can consider the fact that heavy hydrocarbons (HHC) are extracted early in the liquefaction process. This means that the mixture thereafter consists only of lighter components. As the PR has been said to give slightly better calculations than the SRK for hexane, but worse for methane, it seems plausible that the SRK model is the most suited for calculations involving the methane-rich natural gas stream. However, one should keep in mind that the PR CEOS was developed to be applicable to all calculations of fluid properties in natural gas processes, and provide reasonable accuracy near the critical point. According to Penn State (2008) the PR does a slightly better job for gas and condensate systems than SRK and performs somewhat better near the critical conditions.

On the one hand, the scope of this work has not allowed for a study to establish a well-founded choice of fluid property package; one could for example carry out simulations, using different property packages, and compare the results to experimental data. On the other hand, there should not be a need to rank one of the two models over the other; the uncertainties related to the choice of fluid package are considered within the accuracy of the other figures that are used for the energy demand in this work.

The PR CEOS was applied for the simulations in HYSYS.

3.2 Power Import through the National Grid

The national grid infrastructure in Northern Norway had to be looked into, too see whether the proposed energy solution for STII is likely to ensure security of supply.

In building an LNG plant based on power supply from the grid, there are three main factors of importance: First, the grid must have sufficient power transmission capacity. Second, there must be a positive power balance; a high transmission capacity is worthless if there is not enough power available. Third, the imported power must be of sufficiently high quality, i.e. the power supply must be reliable. One must be confident that energy can be delivered at the right power level whenever needed.

To summarize, the security of supply is tripartite:

- There must be transmission capacity in the grid
- There must be a positive power balance, i.e. availability of power
- The power supply must be reliable

3.2.1 Transmission Capacity

Grid capacity calculations must be based on the entire grid infrastructure, and all generators and consumers must be considered. This is a comprehensive task, which can be done for example by Statnett, the TSO. In investigating the capacity of the grid, it was natural to look for reports on the matter from Statnett. Furthermore, a mapping of the potential wind power development has been done by NVE (2008 #2).

It was desirable to see if necessary grid development is likely to happen. Therefore, stakeholders with interest in having a strong grid were identified and their standpoints were gathered. Some actors have commercial interest, some may concern more about what is most socio-economically profitable and some have interests of solely political character. The parties concerned were mapped, and their possibility for influencing on the decision process was assessed.

Important sources for information were press coverage, the EU Renewable Energy Directive and communication thereabout from the Ministry of Energy and Petroleum. Reports from Statnett and NVE regarding grid development plans toward 2025, and possibilities for increased wind power penetration in the power grid were also useful.

3.2.2 Availability of Power

Unless there is availability of power, the plant will not have security of supply even if there is capacity in the grid. The availability of power thus had to be confirmed.

3.2.3 Reliability of Power Supply

First, it was of interest to investigate the reliability of power import from the grid. Second, it was desirable to compare the reliability of power import from the grid with a power supply similar to Train I. Hence, the output from the investigation of reliability should be figures describing the reliability both of power import and of gas turbines.

Gas turbine reliability figures were found by looking up information from manufacturers.

The reliability of power import can be investigated by performing a risk and vulnerability analysis (RIVA). Refer to appendix B for a description of the RIVA approach. The purpose of performing a RIVA is to identify potential risk factors and threats along the way, and to make clear which preventive action that may be taken to avoid disturbances to the power supply. During the work it was realized that this approach was too complex and really more the responsibility of the grid companies. The reliability of power import was rather indicated with basis on selected statistical data from NVE (2008) and Statnett (2008 #2).

3.3 Heat Supply from Gas Furnaces

The proposed energy system for STII includes gas furnaces for heat generation. The most realistic alternative to fossil fuelled heat generation is electric furnaces, which are much less exergy efficient. There will not be any capture of CO2 from the exhaust gas. However, emissions from the heat generation will be offset by wind power, as discussed in section 2.3.3.

The gas fired unit is essentially some kind of a furnace and heat exchange arrangement whose primary function is to efficiently transfer heat from combustion gases to another fluid. Various designs and arrangements of combustion chambers/furnaces/complete boilers exist, and the terminology, which for a large part differ between the U.S and the U.K., will not be discussed here. The service provided is the main focus, namely the utilization of heat energy latent in hydrocarbons to supply different processes with heat energy.

Fuel is combusted together with air, and heat is transferred to heat consumers by heat exchange. The heat exchange depends on the internal geometry of the furnace, the material of which it is made and on the temperature levels. In industry, furnaces often heat a heat transfer fluid (HTF) with high heat transfer efficiency and special additives to inhibit corrosion. This HTF thereafter circulates round the plant to deliver heat where it is needed. At Snøhvit, this heat bearer is hot oil.

Modern furnaces of residential scale have efficiencies of 90 % and upward, i.e. they can deliver that much of the energy latent in the fuel to a secondary fluid. Some models have near total efficiency (Answers, ConsumerReports). Industrial equipment is produced by manufacturers servicing industry and is much larger in size and capacity than residential units. For furnaces of industrial scale, the energy saving potential becomes significant, and measures to increase the efficiency over residential furnace efficiency levels might be cost-effective.

One way of reducing energy loss is to use a low air to fuel ratio in the combustion. By carefully controlling the amount of excess air, i.e. the oxygen concentration, one can reduce the heat retained in excess air, which is lost through the exhaust, and still ensure complete combustion. This is of course also a question of optimum design of combustion chambers and mixing of fuel and air. Oxygen trim controls measure the concentration of stack gas oxygen and automatically adjusts the inlet air at the burner. In general, combustion control in various forms is the key to achieving high efficiency and adds more value as the size of the equipment increases. Moreover, the exhaust gas can be used to pre-heat gaseous fuels and combustion air in a recuperator, see figure 3.5. This reduces the heat loss through the stack, or in other words, increases the utilization of the fuel energy.

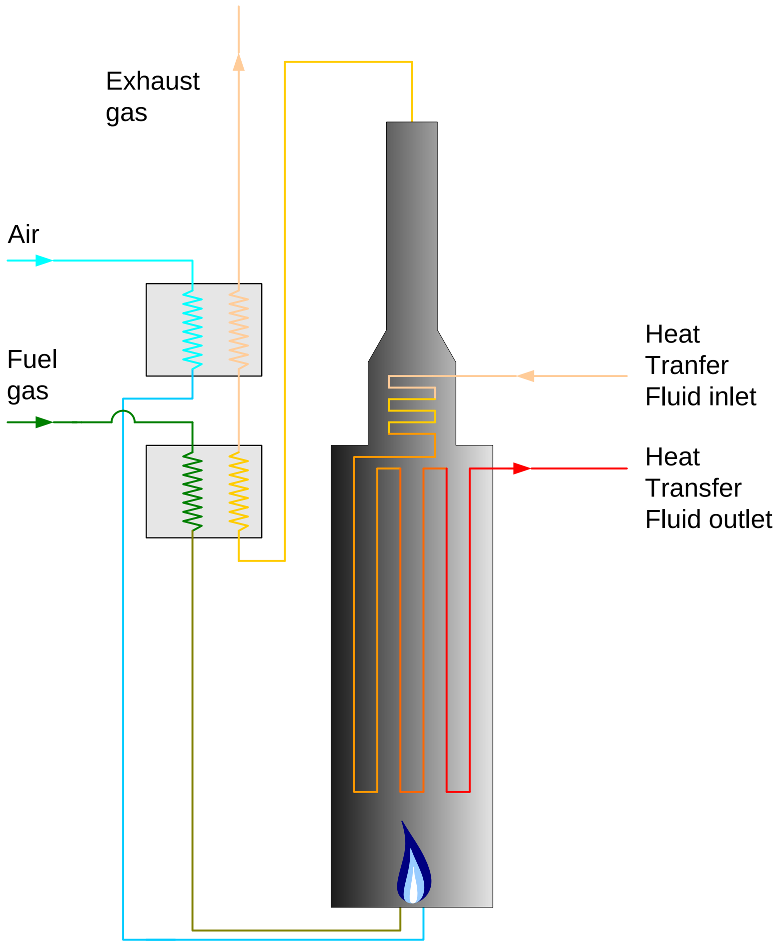


Figure 3.5: Sample illustration of gas furnace

Furnaces of industrial scale were assumed to have efficiencies at least equal to those of residential scale furnaces. An efficiency of 90 % was therefore used in calculations.

A typical furnace based heating system will last about 25 years, though some gas furnaces can last twice that long (IQSD). Heat supply based on this technology should therefore be reliable through the lifetime of STII.

3.4 Offsetting GWP by Wind Power

Significant greenhouse gas emissions will occur due to the STII energy system, CO_2 in particular. The impacts of each greenhouse gas (GHG) is converted to CO_2 equivalents, and the total impact from all GHGs in the following referred to as the global warming potential (GWP).

As discussed in section 2.3, this paper suggests installation of wind power to offset the GWP. The total energy system GWP without wind power is different for each of the six scenarios. This means that the proper fraction of wind power in the energy system must be calculated for each scenario. When these fractions are known, the corresponding rated wind power can be calculated. Finally, a rough screening of all known wind farming projects in the vicinity of STII is performed to identify the most promising projects.

A few topics will be discussed in more detail, to provide for a better understanding of how the wind power will offset GWP:

- Quantification of the GWP of the STII energy system
- Establishing of a reasonable GWP threshold level
- Determination of the capacity factor for wind farming in Northern Norway
- Development of an approach for finding the proper share of wind power for each scenario
- Screening of known wind farming projects

Each of these topics will be elaborated on in the remaining of section 3.4.

3.4.1 GWP of the Proposed STII Energy System

Life cycle assessment (LCA) is a systems analysis tool to identify all the environmental impacts associated with a product, covering the whole life cycle of the product from the extraction of the resources to the final disposal. SimaPro is widely used software for doing LCAs. In particular, it is used by the LCA lab at NTNU. By using this program along with the included Ecoinvent database, it is possible to convert the inventory data for energy production into ten different impact categories, e.g. global warming potential (GWP_{100}) and ozone layer depletion. Only the GWP_{100} impact category is of interest for this paper. GWP_{100} is the net global warming potential integrated over 100 years (Guinée 2002: 187). GWP_{100} will hereafter be referred to as GWP for simplicity. By calculating the GWP, one takes into account the effect of all greenhouse gas emissions over the life cycle of the energy source, and converts the impacts into CO_2 equivalents per unit of energy. This gives a more realistic figure for comparison than just taking into account the direct CO_2 emissions from operation.

GWP of power import

Several approaches can be chosen to determine the GWP of the grid power, but in the end the question is how one interprets the consumption of marginal power. Three different cases were suggested in table 2.1. Case A considers the marginal power as hydro power. Case B considers the marginal power as a Nord Pool market mix, taking into account the national power production and the average effects of power trade with Norway's neighboring countries. Case C considers the marginal power as coal power produced by otherwise idle coal power plants.

The GWP per unit of power consumption can be found for each of these viewpoints using representative modules from the Ecoinvent database in SimaPro.

- Case A uses a module for hydro power that is specific for Norwegian hydro power plants.
- Case B uses a module that includes the share of domestic electricity production by technology and power trade with neighboring countries.
- Case C uses a module for coal power plants that takes into account the net efficiency of hard coal power plants in the NORDEL countries. These countries are Norway, Denmark, Sweden, Finland and Iceland, and were considered representative.

Refer to appendix C for additional details about the relevant modules in the Ecoinvent database.

GWP of heat generation in gas furnaces

Heat generation in gas furnaces is a mature technology with easily measureable impacts. The GWP from a representative industrial scale gas furnace can directly be found in a module in the Ecoinvent database. This module takes into account the combustion of refinery gas. Refer to appendix C for additional details about this module.

GWP of wind power

The GWP of wind power could be found by taking two different approaches. The first approach is to consider how much the European CO_2 emissions would be reduced if more renewable power production were introduced into the Norwegian grid. The second approach is to analyze solely the impacts of wind farming without considering that it replaces power production from other sources. Of the two approaches the former is of the most interest because the wind power is foreseen implemented as a part of the STII energy system, not as a solitary entity.

Recently SINTEF performed a study which analyzed the net environmental gain of implementing more renewable power production in Norway. Their simulations showed that the European CO_2 emissions are reduced with 526 kg per MWh of additional renewable power production in Norway. According to the report the environmental gain could mainly be achieved due to a reduced power import. SINTEF found that the reduced need for power import resulted in less power production based on fossil fuels and thereby reduced CO_2 emissions in other countries (SINTEF 2007). As a conservative estimate, the CO_2 emissions avoided with the introduction of wind power are assumed to correspond to the avoided GWP. In reality, the avoided GWP would probably be even higher, because power production based on fossil fuels has a significantly higher GWP than wind power production.

3.4.2 Acceptable GWP for STII

It is not simple to determine the acceptable GWP for the STII energy system as it depends on what benchmark is used. One could argue that it is reasonable to compare the proposed energy system with a combined heat and power (CHP) plant with carbon capture and storage (CCS). On the one hand, this is appropriate as it is discussed thoroughly as an alternative to the energy system proposed in this paper. On the other hand, it is a very ambitious benchmark, as a CCS is never before built in a large industrial scale. Still, it is significantly better than using the Train I energy system as benchmark, as this is built without any CCS.

By implementing wind power as a part of the proposed energy system it is possible to do better, i.e. achieve a GWP even lower than that of a CHP plant with CCS. This is because wind power has a negative environmental impact, as discussed above.

The total GWP of the proposed energy system is undoubtedly an important parameter for the government when evaluating whether to grant permission for developing STII. For this reason it is suggested to implement wind power to an extent such that the total energy system GWP becomes zero. By doing so one strengthens the chances for obtaining the governmental permission for developing STII.

3.4.3 Wind Power Production Estimate

A mapping of the wind resources in Northern Norway was done in the project thesis preceding this master thesis. The aim was to estimate the average power production from wind farms in the vicinity of STII, and in short, the study resulted in an estimate of the capacity factor (CF); a simple parameter from which one can estimate the production potential of a wind farm in a particular area. The CF indicates how many percent of the rated capacity a wind farm is expected to produce on average over the year. A CF of 39.6 % was found to be representative for wind farming in the vicinity of STII (Bomstad and Nordland, 2008).

According to SWECO (2007) a CF of 23 % is common in continental Europe, compared to 34 % in Norway. Additionally, SWECO states that it could be possible with a CF as high as 46 % at optimal sites in Norway. The discussed capacity factors are summarized in table 3.1.

CF	*Description*
39.6 %	A representative value for wind farming in the vicinity of STII
23 %	A typical value for wind farming in continental Europe
34 %	A typical value for wind farming in Norway
46 %	The CF at optimal sites in Norway

Table 3.1: Capacity factors for wind farming at different locations

3.4.4 Share of Wind Power and Rated Wind Power

The aim with this section is to find the amount of wind power that must be introduced in order to achieve a GWP neutral STII energy system. A mathematical relationship must be derived between the energy demand imposed by STII, the capacity factor of wind power and the GWP threshold. An overview of the parameters relevant for the following derivation is provided in table3.2.

Parameter	*Description*	*Unit*
GWP	Global warming potential	*kton CO_2 eq*
T	GWP threshold for the energy solution	*kton CO_2 eq*
F	GWP per unit for each of the energy sources	*kg CO_2 eq/MWh*
P	Annual power requirements	*MWh/year*
H	Annual heat requirements	*MWh/year*
CF	Capacity factor, wind power	
X	Share of wind power	
1-X	Share of power from the grid	
R	Rated wind power	*MW_{el}*

Table 3.2: Important parameters for determining the rated wind power

A set of indices are needed in addition to the parameters listed above. An overview of the most important indices is provided in table 3.3.

Index	*Description*
i	General Case i
t	Total
f	Gas furnace
g	Grid
w	Wind farm

Table 3.3: Important indices

Share of wind power

The first step of finding the rated wind power is to find the share of wind power of the total power consumption. The following derivation is made for the general Case i. The total GWP for case i, $GWP_{t,i}$, is the sum of GWP for the gas furnace, the power from the grid and the power from wind farms. This must be set equal to the GWP threshold, T, as illustrated in equation 3.3.

$$GWP_{t,i} = GWP_f + GWP_{g,i} + GWP_{w,i} = T \tag{3.3}$$

The GWPs for the gas furnace, the power from the grid and the power from wind farms are found from equations 3.4a-c. These equations factor together the GWP per produced MWh with the amount of energy demanded from each source.

$$GWP_f = F_f \cdot H_t \tag{3.4 a}$$

$$GWP_{g,i} = F_{g,i} \cdot P_{g,i} = \left(1 - X_i\right) \cdot F_{g,i} \cdot P_t \tag{3.4 b}$$

$$GWP_{w,i} = F_w \cdot P_{w,i} = X_i \cdot F_w \cdot P_t \tag{3.4 c}$$

Combining equation 3.3 with equations 3.4a-c, and rearranging, gives an expression for the share of wind power for Case i. The expression is given in equation 3.5. This equation will be used to quantify the share of wind power for all scenarios.

$$X_i = \frac{F_f \cdot H_t + F_{g,i} \cdot P_t - T}{P_t \cdot \left(F_{g,i} - F_w\right)} \tag{3.5}$$

Rated wind power

With the share of wind power known, the rated wind power to be installed can be found for all scenarios. First, the annual power requirements from wind power for Case i must be expressed by combining the share of wind power, X_i, with the total power requirement for STII, P_t. The rated wind power required for case i, R_i, can then be found by dividing the annual power requirements from wind farming with the capacity factor CF and the total number of hours in a year (8760 hours, leap years exempt). The final equation for finding the rated wind power is shown in equation 3.6. This equation will be used to find the rated wind power for all scenarios.

$$R_i = \frac{X_i \cdot P_t}{CF \cdot 8760\ hrs} \tag{3.6}$$

3.4.5 Criteria for Selection of Wind Farms

This section includes the methodology for a rough screening of the known wind farming projects in the vicinity of STII. The purpose is not to identify and suggest the single most attractive wind farming project, it is rather to narrow down a long list of known projects to a shorter list of suitable projects. This is done with basis in a few comprehensible criteria. A complete list of wind farming projects notified to the Norwegian Water Resources and Energy Directorate (NVE) are available through their web pages (www.nve.no). The projects are sorted in six categories:

- Notification sent to NVE
- Applied for concession to NVE
- Concession granted, not yet operating
- Operating
- At rest (critical conflict with the radar installations of the Norwegian Armed Forces)
- License denied

Only the three first categories are of interest for the screening process as these have the greatest potential in terms of being a part of the STII energy system. The remaining three categories are left out of the screening process. The criteria listed below will be used for the screening. The alternatives are provided below each criterion. The corresponding scores are found in the brackets behind each alternative.

1. Location near Melkøya
    - Western Finnmark (west of Porsangerfjorden) [3]
    - Eastern Finnmark, Troms and Northern Nordland (north of Tysfjord) [2]
    - Southern Nordland [1]
2. Maturity in the application process
    - Concession granted, not yet operating [3]
    - Applied for concession to NVE [2]
    - Notification sent to NVE [1]
3. Acceptable grid situation
    - Along the 420 kV power grid from Ofoten through Balsfjord to Hammerfest [3]
    - Not along the 420 kV power grid (for example Lofoten) [1]

In addition, all projects had to be above a rated capacity of 40 MW_{el} to be considered. Projects with a lower rated capacity are left out of the screening process. Additional criteria could have been used in a more thorough screening, such as a low conflict level with tourism and reindeer husbandry. However, this kind of information is known just for a few projects and is therefore left out of the screening.

The criteria are weighted equally in the screening process. All projects with an average score of two or higher will end up in the final list of the suitable projects in terms of being part of the STII energy system. Production estimates will also be performed for each of the projects in the final list. The production estimates will be based on a CF of 39.6 %, which is found representative for wind farming in the vicinity of STII, as discussed in section 3.4.3.

3.5 Investment Analysis of the STII Energy System

The proposed energy system must prove economically viable to be of interest for SH. An investment analysis must therefore be done to quantify the key economic figures of the STII energy system. The tool for doing the analysis is a self developed investment model made in Microsoft Excel.

There are three targets for the investment analysis. The first target is to estimate the net present cost (NPC) of the STII energy system. The second target is to convert the calculated NPC into break even heat and power prices for each scenario. The third target is to provide a sensitivity analysis identifying what parameters impact the results the most.

Four topics will be covered in the remaining of section 3.5:

- The approach for the investment analysis
- A brief explanation of the tax systems implemented in the investment model
- A discussion of the most important assumptions for the investment analysis
- A discussion of the investment model and the desired outcomes of the analysis

3.5.1 Approach

Six different scenarios

The investment analysis will be based on six different scenarios covering two dimensions. The first dimension is the origin of the grid power. Three different sets of assumptions are classified as Case A, B and C as discussed in section 2.3.1. The share of wind power in the energy system will be different for each of the three cases. The other dimension of the scenarios is the STII train size. Two different train sizes will be investigated; 50 % and 70 % STII of the full LNG production capacity of Snøhvit Train I.

Combining the two dimensions, investment analyses will be performed for a total of six different scenarios. The scenarios are named with a logical system; for example, Case B and train size 70 % will be referred to as scenario B.70. The six different scenarios are illustrated in figure 3.6.

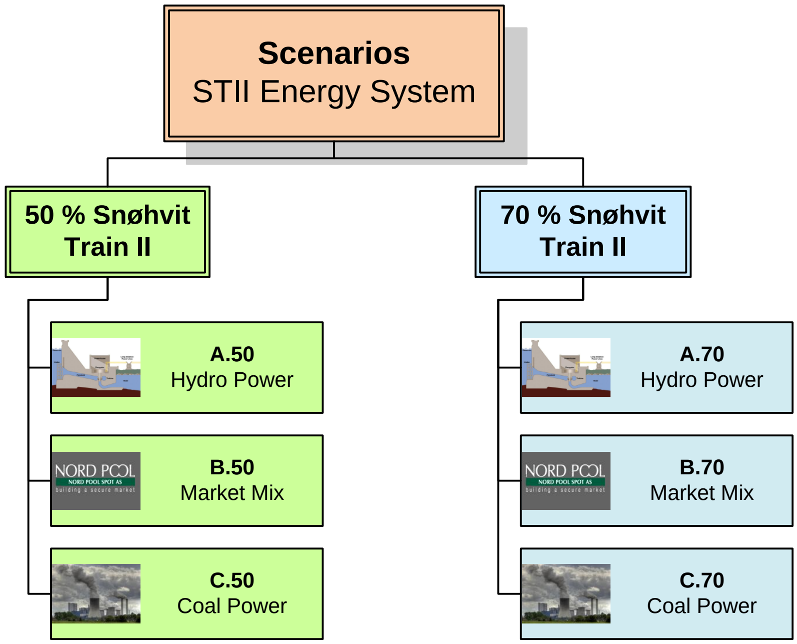


Figure 3.6: Scenarios for the STII energy system

Heat and power supply analyzed separately

The heat supply is defined such that it includes all associated expenses with the gas furnaces, i.e. the capital and operational expenses of the gas furnaces, the fuel gas and environmental taxes.

The power supply is defined such that it includes all other expenses of the STII energy system, i.e. the capital and operational expenses of the wind farms, investments in upgrading the grid, fees for connecting STII to the grid and the cost of buying power from the Nord Pool Spot market.

The heat and power supply are treated separately in the investment analysis for at least three reasons. First, heat and power are distinguishable products which have different values. The cost of each of these products is most easily found if the heat and power supply are analyzed separately. Second, due to different tax regimes for the heat and the power supply they should be analyzed separately in order to achieve more realistic results. The tax systems are further discussed below. Third, the workload is decreased because the heat supply only differentiates between the two train sizes analyzed, not Case A, B and C. This means that the power supply must be analyzed for all six scenarios, while the heat supply only needs to be analyzed twice. Although heat and power supply are treated separately, the final post tax results will be consolidated to find the total energy system cost.

3.5.2 Tax Systems

Upstream and ordinary tax regime

Upstream petroleum activities are subject to tax according to the ordinary Norwegian corporation tax system, with some special deviations and the addition of a special tax for upstream activities. The ordinary Norwegian corporation tax is currently 28 %, while the special tax for upstream activities is currently 50 %. This means that upstream activities have a marginal tax rate of 78 % (NPD 2006). The upstream tax bracket will hereafter be referred to as the *upstream tax regime*, while the ordinary Norwegian corporation tax regime will be referred to as the *ordinary tax regime*.

The heat supply based on gas furnaces is undoubtedly in the upstream tax regime. This can be supported by the fact that the CHP for Train I is defined in the upstream tax regime. It is uncertain whether the Norwegian government will define the power supply in the upstream or in the ordinary tax regime. However, as a baseline the power supply is defined in the ordinary tax regime. The reasoning for this is further discussed in section 5.5.1.

Depreciation

Depreciation is an allocation of the cost of an asset over a period of time for accounting and tax purposes. Depreciation is a non-cash expense that is added into net income to determine cash flow in a given accounting period (Goleman et al. 2006: 1467). Normally investments in the offshore tax regime are depreciated linearly over six years. However, special considerations apply to LNG projects which are allowed to depreciate all investments linearly over three years. This results in an annual depreciation rate of 33.33 % (Wood Mackenzie, no date). Depreciations in the ordinary tax regime are far more complicated to calculate as all expenses must be organized in asset groups. For wind power three asset groups are relevant; asset group d, g and h. In these groups the annual depreciation rate varies between 4 and 20 % (Skattedirektoratet 2009). However, it is not easy to allocate expenses into these asset groups with the detail level chosen for this paper. For simplicity it is assumed that investments in the ordinary tax regime can be depreciated linearly over 10 years. This results in a depreciation rate of 10 %. This does not give exact post tax results, but it will give a realistic indication of the tax effects.

Uplift

Uplift is deducted when calculating the income eligible for special tax. The purpose of uplift is to ensure that normal returns are not subject to special tax. The uplift rate is 7.5 % of the cost price of the depreciable business assets, annually over four years from the year the investment is made. Uplift only applies to the upstream tax regime (NPD 2006).

Losses carried forward

In the upstream tax regime, losses may be carried forward from one year to the next, with interest. The current interest rate for losses carried forward is 4.1 %, and is applicable to both depreciation and uplift (Skatteetaten 2009). Losses may also be carried forward in the ordinary tax regime, but without interest.

Tax calculation

According to the Norwegian Petroleum Directorate the tax calculation can briefly be described as follows for the offshore tax regime (NPD 2006):

Operating income
- Operating expenses
- Linear depreciation (depreciation rate: 33 1/3 % per year)
- Environmental taxes (CO_2 and NO_x)
- Losses carried forward from previous years
= Corporation tax base (tax rate: 28 %)
- Uplift (7.5 % of the investment for 4 years)
- Excess uplift carried forward from previous years
= Special tax base (tax rate: 50 %)

The tax calculation in the ordinary tax regime differs slightly from the offshore tax regime. Uplift and special tax, and environmental taxes do not apply, and the depreciation rate is 10 % per year. Hence, the tax calculations can briefly be described as follows:

Operating income
- Operating expenses
- Linear depreciation (depreciation rate: 10 % per year)
- Losses carried forward from previous years
= Corporation tax base (tax rate: 28 %)

3.5.3 Assumptions

This section is a discussion of the most important assumptions for the investment analysis. Note that the expenses below are provided in 2009 NOK.

Project lifetime

The production from STII is forecasted to start in January 2016. The economical and technological lifetime of both STII and the wind farms is estimated to be 25 years from the start of operation. It is assumed that all capital expenditures (CAPEX) are payable in 2015, while the operational expenditures (OPEX) are payable annually throughout the lifetime of STII. All payments are assumed payable by the end of the year they occur.

Nord Pool Spot market price

The electricity price in the time span of STII is highly uncertain, but has in recent years increased. The forward contracts traded at Nord Pool is the markets own evaluation of the future electricity price, and the most remote contracts traded at Nord Pool are the three year forward contracts. Beyond that the electricity price is not easily observable. The three year forward contracts for electricity was, on a six month average, traded at approximately NOK 450 per MWh as of September 2008 (NVE 2008). It is assumed that the electricity price stabilizes on this level and this price is used as baseline in the investment analysis.

Natural gas price

Determination of the natural gas price is not straightforward, especially when the gas used is produced onsite. The onsite natural gas consumption is often treated as stranded gas, meaning that it cannot otherwise be sold until the tail of the LNG production. This is because it is assumed that the plant is producing at maximum capacity. After discounting a sale at the tail of the production to present value, this gas has approximately no value and the price is set very close to zero. The market price may also be chosen, but is not very realistic considering the stranded gas argument discussed above. According to SH it is fair to use a value of NOK 0.60 per Sm^3 for the natural gas consumed by the gas furnaces in the energy system. This is only a fraction of the market value, but still significantly higher than the stranded gas value. It may appear artificial to put a price on the natural gas considering that the transaction is strictly internal in the STII project; SH is both the buyer and the seller of the natural gas. However, a proper price must be set in order to quantify the total energy system cost for both tax purposes and internal accounting.

Capital expenditures (CAPEX)

An expense for acquiring, producing or enhancing fixed assets is considered to be a CAPEX (Goleman et al. 2006: 1427). According to NVE the average CAPEX for wind power was approximately MNOK 12.8 per MW_{el} in 2007 (NVE 2008). Adjusted for 2 % inflation per year this corresponds to MNOK 13.3 per MW_{el} in 2009. This includes the turbine, foundation, internal grid, local infrastructure and projecting costs. External grid improvements come in addition and are roughly estimated by SH to be MNOK 1 per MWel. The proposed energy system requires reinforcement of the power transmission system between Balsfjord and Hammerfest. The SH share of this grid reinforcement is roughly estimated to be 120 MUSD (Bomstad and Nordland 2008). This corresponds to approximately MNOK 785 with the exchange rates as of May 1st 2009. According to SH the gas furnace CAPEX is estimated to approximately MNOK 11.2 per MW of heat required by STII.

Operational expenditures (OPEX)

Operational expenditures (OPEX) are the counterpart to CAPEX. The OPEX presented here are the ongoing expenses for running the proposed energy system. According to NVE the estimated OPEX for wind farming is approximately NOK 130 per MWh. This includes expenses to operation and maintenance, feed-in tariff to the grid, insurance and compensation (NVE 2008). According to Statnett, the annual cost of connecting STII to the grid is approximately NOK 129,000 per MW_{el} (Statnett 2008). According to SH the gas furnace OPEX is about Euro 1.2 per MWh (Bomstad and Nordland 2008). This corresponds to approximately NOK 10.40 per MWh with the exchange rates as of May 1st 2009.

Environmental taxes (CO_2 and NO_x)

Burning of natural gas for power production is subject to a CO_2 tax. Currently the CO_2 tax is NOK 0.46 per Sm^3 of gas burned. Emissions of NO_x are also subject to a special tax. Currently the NO_x tax is NOK 15.85 per kg of NO_x emitted to the atmosphere (NPD 2009). In addition, oil and gas companies must buy CO_2 quotas for all their emissions through the European Union Emission Trading Scheme. However, the proposed energy system is designed such that the GWP is zero due to implementation of wind power. With a GWP of zero one can make a strong argument that SH should be exempt from buying CO_2 quotas in addition to the CO_2 tax.

It is assumed that SH must pay the environmental taxes, but are exempt from buying the CO_2 quotas.

Rated wind power

The approach for finding the share of wind power, and thereby the rated wind power for each scenario is discussed in section 3.4, while the results from the analysis are presented in section 4.4. The rated wind power from this analysis will be used as an input for the investment analysis.

Inflation and discount rate

The value of future cash flows cannot be directly compared because money in hand today is more worth than money received in the future. To account for the time value of money a discount rate of 8 % will be used in the investment analysis. This is the standard discount rate used by SH for screening of projects. In addition it is assumed an inflation rate of 2 % to account for a sustained increase in Norway's general level of prices. The annual inflation is expected to last over the lifetime of the project.

No governmental subsidies for the wind farms

As the heading indicates, the investment analysis will be based on no governmental subsidies for the energy system. Even though the wind farms might be eligible for governmental subsidies, the political framework is considered too unpredictable in the time span of STII to be taken into account. This makes the investment analysis conservative as future subsidies only contribute in the positive direction for the energy system.

3.5.4 Desired Outcomes of the Investment Analysis

The investment model takes into account the elements discussed above, i.e. the different tax systems and the assumptions. The approach described below applies to each of the six scenarios discussed above.

Net present value (NPV) method

The present value is a representation of today's value of money to be received in the future assuming that the money can be invested today at a given discount rate. The NPV method is applied to compare sums of cash to be received or paid in the future. The NPV is the difference between the present value of the income and the present value of the costs. A positive NPV means that the project should be accepted while a negative net present value means that the project should be rejected (Droms 2003: 187).

Net present cost (NPC) of the energy system

The first step of the investment analysis is to calculate the NPC of the energy system. The NPC is found by implementing the costs in a NPV analysis, while leaving the income at zero. The NPC is calculated to understand the magnitude of the energy system cost. This is useful because the energy system does not directly generate money; it is rather a necessity for the LNG processing and liquefaction facility which in turn generates money to pay the energy system cost. The NPC analysis gives insight in whether SH must take on additional costs by implementing wind power in the energy system.

Break even (BE) heat and power prices

Income is added to the investment model as a second step of the investment analysis by defining a price on the energy delivered by the energy system. The heat and power prices are found exactly such that the NPV of the entire energy system becomes zero. These prices are hereafter referred to as *BE heat* price and *BE power price*, respectively. As mentioned above, the calculations of the break even energy prices are done separately for the heat and power because heat and power are distinguishable products with different values.

Sensitivity analysis

A simple sensitivity analysis can be performed by changing parameters in the investment model one by one while recording the movements. This is done to identify the most critical parameters. The basis for the sensitivity analysis is the model where the costs are exactly balanced by the income, and sensitivity analyses are done for each of the six scenarios.

CHAPTER 4: RESULTS

4.1 Heat and Power Requirements for STII

4.1.1 Energy Figures for Snøhvit Train I

Table 4.1 lists the Snøhvit Train I energy requirements. Only the largest heat consumers are listed, together with the total demand, i.e. the total demand is not the sum of the figures listed for each subsystem. The values in table 4.1 are design values as figures for the actual power consumption has not been available. It is likely that the design values deviate from the actual power consumption.

Efficiencies have been taken into account when developing table 4.1. The power figures are thus not the process demand, but rather the consumption of the electric drives, i.e. the power that must actually be supplied from the grid. First the rated power of each component was found, and then the respective component efficiencies were applied to find the power figures that must actually be consumed for them to deliver the design duty. Example: A pump duty of 1000 kW is needed. The pump however converts only 95 % of the power into mechanical work on the fluid, and the actual power need is thus 1000 kW /0.95 which is about 1053 kW.

Table 4.2 summarizes the content of Table 4.1 and identifies the energy demand for each subsystem as a percentage of the total energy demand. This makes it even clearer which subsystems are the largest consumers of heat and power. As stated above only the largest power and heat consumers are listed, i.e. the total heat and power demand is not the sum of the figures listed for each subsystem. Note that the liquefaction subsystem amounts to about two thirds of the entire power demand and that gas condition amounts to more than two fifths of the heat demand.

SNØHVIT TRAIN I ENERGY REQUIREMENTS			*Power*	*Heat*
			[MW_{el}]	*[MW]*
Full capacity Snøhvit Train I			209.7	206.0
SUBSYSTEM	**SERVICE**	**DESCRIPTION**		
Reception				
	MEG Recovery	Total heat demand		12.1
		El. Resistance Heaters + 40 Pump & Compr. Motors	0.9	
	Feed gas compression	FUTURE EXPANSION	23.8	
Gas conditioning				
	CO_2 Removal	Total heat demand		76.5
		MDEA Pump Motors	2.0	
	CO_2 Drying & Compression	CO_2 Compressor and Pump Motors	9.5	
	Water Removal	Drying of Feed Gas		10.0
		Regeneration Gas Blower Motor	0.2	
Liquefaction				
	Natural Gas Liquefaction	Precooling Cycle Compressor Motor	57.5	
		Liquefaction Cycle Compressor Motor	27.7	
		Subcooling Cycle Compressor Motor	57.8	
		LNG Pump Motor	0.2	
		El. Gen. Sub-cooling Cycle Liq. Exp. Turbine	-0.8	
		El. Gen. LNG Expansion Turbine	-1.4	
	HHC Removal	Reboiler heat demand		7.1
Nitrogen Removal				
	Nitrogen Removal	N2/CH4 Compressor Motor	15.4	
Fractionation				
	Condensate Treatment	Total heat demand		36.9
		Stabiliser OVHD Compressor Motor	7.0	
Storage and Loading				
	LNG Storage	LNG Loading and Fuel Pump Motors	2.4	
	Condensate Storage	Condensate Loading Pump Motors	0.8	
	LPG Storage	LPG Loading Pump Motors	0.6	
Energy Utilities				
	Power utility related	Anti Icing for Gas Turbines		5.3
		Gas Pre-Heater		10.4
		Fuel Gas System		2.4
	Heating	Tempered Water		6.6

Table 4.1: Snøhvit Train I energy requirements and largest consumers

Train I Energy figures per subsystem				
	POWER, incl. ageing		HEAT, new plant	
LNG plant total	213.9	MW	206.0	MW
Subsystem	**[MW_{el}]**	**[% of total]**	**[MW]**	**[% of total]**
Reception	0.9	0	12.1	6
Gas Conditioning	12.0	6	86.5	42
Liquefaction	143.8	67	7.1	3
Nitrogen Removal	15.7	7		
Fractionation	7.2	3	36.9	18
Storage and Loading	3.9	2		
Energy Utilites			24.6	12

Table 4.2: Summary of Train I energy figures by subsystem

4.1.2 Reduced Energy Requirements with the Proposed Energy System

It is presupposed that the fuel gas system for the furnace arrangement is equivalent to that of the gas turbines in train I, i.e. there is no need to pressurize the fuel. Conferring with table 4.1 it becomes evident that heat needed for the energy utilities is quite significant for train I. This will not be the same for STII as there will be gas furnaces instead of gas turbines. STII will require much less heat for these purposes. Without going into detail STII was assumed to require one fourth of what Train I does for the same purpose, a guesstimate that was confirmed reasonable by the supervisor. The expected energy demand for the energy utilities for STII can be found in table 4.3.

Energy saving potential	*Train I*		*STII*
Heat demand	**[MW]**	**-> Reduction [%] ->**	**[MW]**
Anti Icing at air intake	5.3	75 %	1.3
Gas Pre-Heater	10.4	75 %	2.6
Fuel Gas System	2.4	75 %	0.6
Tempered Water	6.6	75 %	1.6

Table 4.3: Heat demand for energy utilities for full capacity trains

4.1.3 Simulations

Simulation results are more uncertain the closer one gets to the critical point, refer to section 3.1.2. The converged simulations included HHC removal in a distillation column with an operating pressure of 59 bars. This is close to the critical pressure of the NG stream after the column, which was about 60.9 bars, depicted by the yellow point on the phase envelope in figure 4.1.

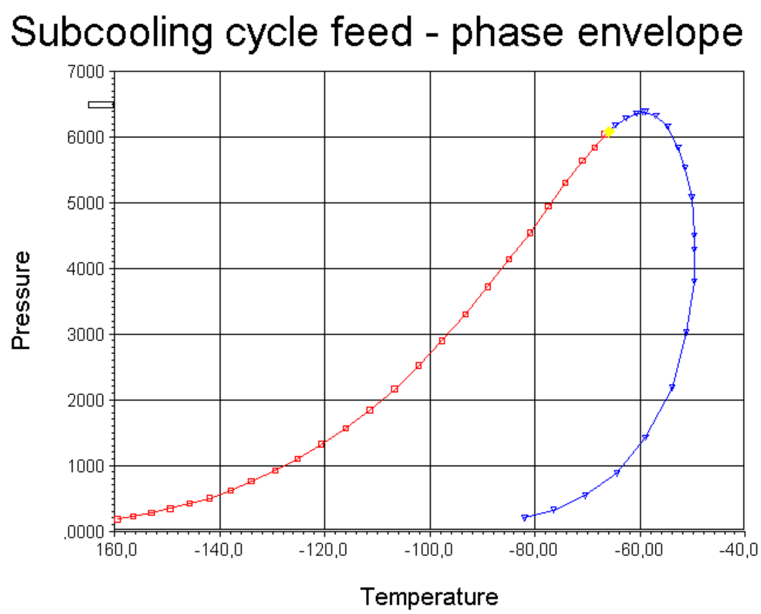


Figure 4.1: Phase envelope for natural gas stream after HHC removal (HYSYS)

Simulation results for both train sizes are summarized in table 4.4. Note that the simulated heat demand only constitutes 3 % of the total heat demand of the plant, and is not used to estimate the STII heat demand. The power figures in table 4.4 make basis for the power requirement estimates for STII.

Simulation results	***70 % STII***	***50 % STII***
Power demand		
Natural Gas Liquefaction		
Precooling Cycle Compressor Motor	30.1	21.8
Liquefaction Cycle Compressor Motor	18.7	13.4
Subcooling Cycle Compressor Motor	31.6	22.6
LNG Pump Motor	0.1	0.1
El. Gen. Subcooling Cycle Liq. Expansion Turbine	-0.9	-0.7
El. Gen. LNG Expansion Turbine	-0.8	-0.6
Sum	**78.7**	**56.5**
Heat demand		
HHC Removal		
Reboiler heat demand	5.0	3.6
Sum	**5.0**	**3.6**

Table 4.4: Results from HYSYS simulation of the liquefaction subsystem

4.1.4 Key Energy Figures for STII

The energy figures for STII, which are input to the investment analysis, were calculated by equation 3.1 and 3.2, and are reproduced in table 4.5 and 4.6. The plant was assumed to be in operation 330 days annually.

Key power figures			***Unit***
50 % STII	Power demand	101.4	MW_{el}
	Annual power consumption	803.1	GWh
70 % STII	Power demand	141.4	MW_{el}
	Annual power consumption	1,119.9	GWh

Table 4.5: Key power figures for STII

Key heat figures			***Unit***
50 % STII	Heat demand	93.8	MW
	Annual heat consumption	742.9	GWh
70 % STII	Heat demand	131.3	MW
	Annual heat consumption	1,039.9	GWh

Table 4.6: Key heat figures for STII

4.1.5 Possible Reduction in Energy Demand by Altering Process Design

By altering the process design it might be possible to reduce the STII energy demand compared to Train I. The main emphasis in this paper has been to investigate the biggest consumer as it is assumed that these have the largest potential for reductions. Table 4.2 shows that the Liquefaction subsystem is the largest power consumer; it constitutes two thirds of the total consumption. Moreover, the only consumer in the Nitrogen Removal subsystem, namely the NRU, has a significant power demand which origin from the decision of removing N_2 from the flash gas.

The most significant heat consumers are the Gas Conditioning, the Fractionation and the Energy Utilities. The Gas Conditioning demand is mainly that of the amine based acid gas removal; more precisely the regeneration of solvent in the CO_2 removal process. The stripping of CO_2 from the MDEA is endothermic, and as the foregoing exothermic absorption only generates a small part of this heat, regeneration heat must be supplied from an external source. Other ways of removing acid gas from a natural gas stream exists. The Fractionation includes several distillation columns, and the boiler duties are considered not to represent any saving potential. The heat demand for the STII Energy Utilities is expected to decrease in the order of 75 % compared to the STII energy system, as discussed in section 4.1.2.

The heat demand of the Liquefaction subsystem is due to the integrated NGL extraction. Many other cooling processes and configurations exist, and could alter the energy demand.

The subsystems that have significant potential for reduced energy demand are picked in table 4.7.

Subsystem	***Power***	***Heat***
Reception		
Gas Conditioning		✓
Liquefaction	✓	✓
Nitrogen Removal	✓	
Fractionation		
Storage and Loading		
Energy Utilites		✓

Table 4.7: Energy saving potential by subsystem

Four subsystems are pointed out in table 4.7. The potential energy reductions for the energy utilities are already discussed. The remaining three are discussed in more detail in the following. These three subsystems are Gas Conditioning, Liquefaction and Nitrogen Removal.

Gas conditioning

The potential for reduced heat demand in connection with CO_2 removal at Snøhvit was investigated in a project and master thesis in 2007-2008. This work investigated the possibility to remove acid gas in a cryogenic process instead of the amine based process. The most suited cryogenic process was found to be the Ryan Holmes process, based on its technological maturity and its separation qualities. It can meet the LNG CO_2 specifications, it does not entail significant loss of hydrocarbons to the CO_2 stream, and it is extremely flexible with regard to varying operational conditions (Østerbø 2008).

Østerbø concluded that the potential for heat energy savings was offset by the extra power need imposed by the cooling demand of the cryogenic process. A STII based on cryogenic CO_2 removal would require 5 MW less heat than train I, but as the heat transfer happens at a lower temperature, there would be a considerable potential for process integration. By changing from an amine based CO_2 removal process to the Ryan Holmes process, the heat demand of STII would be approximately 53 MW lower than that of train I. However, according to Østerbø the shifting from amine based to cryogenic acid gas removal requires 54 MW more power from the cooling compressors. Hence it was concluded that the energy saving potential was low.

Liquefaction

Presupposing that the Statoil-Linde MFC process is chosen also for STII, the largest power saving potential lies in optimization. This is a comprehensive task and has been out of the scope of this work. However, power and heat demand can also be altered by changing the process configuration. This could for example apply to the HHC removal, which in Train I is integrated in the liquefaction plant, in between the pre-cooling in a distillation column. The condenser cooling energy is provided by the pre-cooling cycle, while the reboiler energy must be supplied by a heat source. An alternative configuration would be to move HHC removal upstream of the liquefaction plant, as part of the gas conditioning. This makes the configuration less complex and the energy balance might be different. Upstream HHC removal could be achieved by depressurization, separation and recompression, and would not need a heat supply at all. The gas stream can also be cooled by the cooling cycles before separation in order to reduce the need for depressurization, thereby reducing the power demand for recompression. Some of the recompression work can be taken from the expander shaft, but an extra compressor would be needed to lift the pressure sufficiently. Upstream NGL extraction might make it advantageous to cool the natural gas at a higher pressure.

In short, the reconfigured process would have had to be optimized with respect to many degrees of freedom.

Nitrogen removal

The NRU can be avoided if the entire flash gas stream can be utilized to fuel the gas furnaces of STII.

Using flash gas with high nitrogen content will impose a need to carefully design the combustion system, because of the low heating value. However, this can be solved. The use of nitrogen-rich flash gas should not influence on the NO_x emissions, as also the combustion air is rich in nitrogen. The thermal energy available to the heat transferring fluid from combustion of the entire flash gas flow was calculated from equation 4.1.

$$\dot{Q}_{furnace} = \eta_{furnace} \dot{Q}_{flashgas} = \eta_{furnace} \dot{m}_{flashgas} \sum_{components\ i} n_i \cdot LHV_i \tag{4.1}$$

On the one hand, if the available thermal energy in the flash gas is lower than the STII heat demand, the flash gas stream could be mixed with gas from just after the slug catcher to obtain sufficient amounts of fuel gas. On the other hand, if the heating energy available from the flash gas is much higher than the heat demand of STII, one must either run combustion at lower efficiencies, thereby wasting energy, or treat the gas.

The flow rate and composition of flash gas were taken from the HYSYS simulations that are described in section 4.1.3. Refer to appendix A for tabulated data. The flash gas was assumed to be available at 25 C, meaning that lower heating values at 25 C were applicable.

Heat energy			Unit
50 % STII	Heat energy in flash gas	150.4	MW
	STII demand	93.8	MW
70 % STII	Heat energy in flash gas	210.6	MW
	STII demand	131.3	MW

Table 4.8: Thermal content of flash gas stream vs. STII heat demand

The heat available in the flash gas is more than threefold the heat demand of STII. Since the flash gas flow rate is too high, the gas must be treated.

If the NRU had been avoided, through the use of flash gas in the gas furnaces, some extra power consumption would have been induced by the need to compress the fuel gas. Because of the necessity to treat the gas, power consumption of the Nitrogen Removal subsystem was in this work assumed linear to that of Train I instead of being subtracted from the Train I energy figures.

4.2 Power Import through the National Grid

4.2.1 Security of Supply

There are many stakeholders in up-scaling the grid voltage to 420 kV from Balsfjord to Hammerfest. These stakeholders range from energy and petroleum companies, to developers of wind power to local industry. Industrial and commercial development is in the interest of the public, both through the creation of job opportunities locally and the property tax incomes to the municipalities. Not reinforcing the grid would mean that new petroleum discoveries cannot be supplied with power from the grid, or alternatively, that business development will happen at a slower pace. Moreover, from an environmental point of view, new petroleum installations are best supplied from the grid rather than from gas fired utilities.

Statnett has found that reinforcements are not socio-economically profitable without new power take-off in Finnmark, i.e. they do not recommend a strengthening of the grid only for the purpose of developing new power generation for export. However, with STII being realized, new consumption is readily in place, and with grid reinforcements it becomes possible with more wind power in the region.

Value could be added to utilization of the renewable resources in Northern Norway in connection with the EU's Renewable Energy Directive (RED). This was agreed by the EU Parliament in December 2008 and becomes operative 20 days after it is published in the EU Official Journal in the spring, 2009. The Directive is a bid to boost the share of renewable energy in the block's energy mix to increase from 8.5 % to 20 % in 2020. Each of the 27 member countries is to achieve an increase by 5.5 % from 2005 level, and the rest is calculated based on each country's GDP to achieve the common goal of 20 %. *The RED shall be implemented within 18 months after it comes into force, i.e. in October 2010 (CEC 2008).*

What directives such as the RED means for Norway depend on negotiations with the EU and within the European Economic Area (EEA). In the end of January 2009, Norway's Minister of Petroleum and Energy, Terje Riis-Johansen, stated that the RED is relevant to the EEA, and is therefore to apply also to Norway (Bellona 2009). This makes it clear that there should be no doubt that Norway will commit to the same 2020-obligations as the EU member do. Riis-Johansen made it clear that the RED carries a lot of opportunities for Norway, particularly within trading in clean energy. He added that wind power projects that were not technologically and economically feasible till now, could be realized under the new conditions (TU 2009).

For Norway apart, the share of renewable in the energy mix is already 58 %. If Norway is to increase the share of renewables in its energy consumption in line with that of the EU members, it would mean that 72 % should come from renewables in 2020. With no increase in the consumption, this would entail new renewable production of 32 TWh. With no increase in renewable production, it would require the consumption to be reduced by 44 TWh. The potential for new production from hydro and wind is approximately 30 TWh. All these numbers are according to NVE (2009).

4.2.2 Transmission Capacity

With the start-up of Sydvaranger Gruve AS, near Kirkenes, and the extraction of oil from the Goliat field, which is partly based on power import from the grid, the utilization of the national power grid in Finnmark is complete. The grid voltage level north of Balsfjord in Troms, up to Varangerbotn in Finnmark, is only 132 kV. This makes it the weakest part of the national grid in Norway. The grid thereby curbs the industrial development in Finnmark*, and reinforcements must come in place in order to secure the power transmission capacity needed for further industrial development of any type (TU 2009 #2).*

The grid must be able to deliver enough energy, at the desired power level, throughout the year. With the grid as it is today, there is not enough capacity.

In May 2009 Auke Lont, the CEO of Statnett, announced that Statnett would now speed up the work with reinforcing the national grid from the Narvik area and to Hammerfest (Statnett 2009). A license application for the northernmost part of the line, i.e. from Balsfjord to Hammerfest, will be handed in before the summer of 2009. An application for license for the installation of the 420 kV line from Ofoten to Balsfjord will be sent to the authorities within the end of 2009. Statnett will now also start the planning of a new transmission line from Hammerfest to Varangerbotn in Eastern Finnmark. Lont added that these grid reinforcements will make possible a reduction of emissions from the petroleum sector and the realization of wind power projects.

A closer look on the grid in Northern Norway is reproduced in figure 4.2.

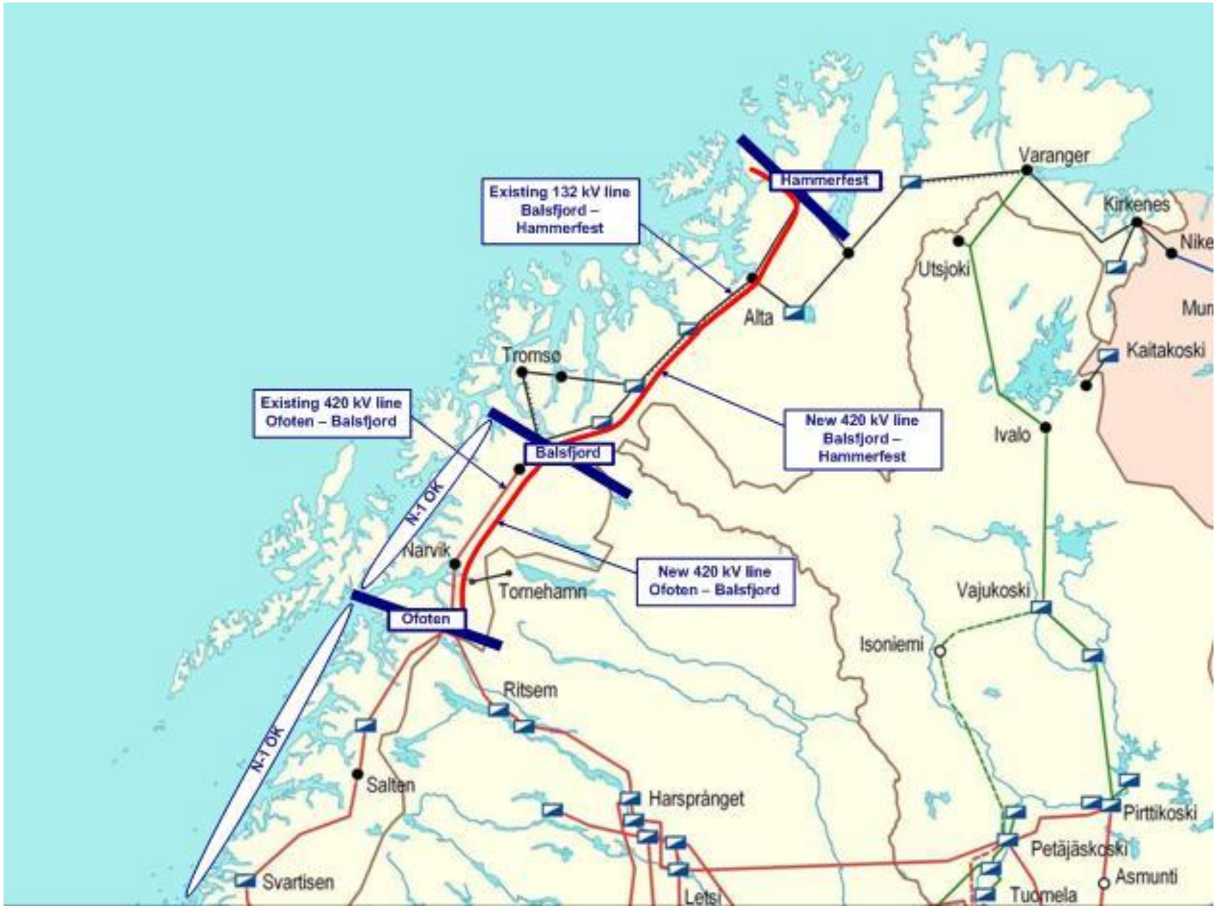


Figure 4.2: Power grid in Northern Norway (Nordel 2008), with remarks

With the grid reinforcements which are underway and seem likely to come in place, capacity will be sufficient for a STII. Statnett has calculated that the capacity for new wind power generation in Finnmark will by about 500 MW with the new transmission line to Hammerfest (Statnett 2008 #4). The capacity of today, for new wind power, is 120 MW.

With new power take-offs in Finnmark, such as represented by the Sydvaranger Gruve AS, the Goliat project and STII, the potential for wind power increases. This is because much of the power will be utilized locally. A rough estimate of this increase would be that for each MW new power take-off, one makes place for 2 MW of new wind generation (Bergvoll). This has to do with the variation in wind generation over the year, and its correlation to hydro power production. Although calculations must be performed based on a detailed grid, including all new grid lines and all new producers and consumers, to achieve good figures on the capacity for power supply and the capacity for increased wind power penetration, one can conclude that the capacity will be sufficient to supply STII, either by power generated by new production in Finnmark or exported from further south.

In Nordel's grid development master plan of March 2008, the Ofoten-Balsfjord-Hammerfest 420 kV line was identified as one of eight projects of importance to the Nordic Power System (Nordel 2008 #2). It was recommended that the national TSO, Statnett, should start the planning of this reinforcement. Petroleum related consumption and the development of wind power were identified to be the main driving forces for an extensive improvement of the grid in Mid and Northern Norway.

The possible increase in power consumption in connection with STII and other petroleum activity in Northern Norway, and the desire to develop renewable energy in that region, were some of the most important challenges that were addressed by Statnett's grid development plan towards 2025 (Statnett 2008 #3). A new Ofoten-Balsfjord-Hammerfest 420 kV connection to supply STII was explicitly listed as part of Statnett's main strategy to ensure sufficient transmission capacity to and within the region.

4.2.3 Availability of Power

It has been found that the power balance in Northern Norway is sufficient to supply STII (Bomstad and Nordland 2008). Also according to Statnett, there is a surplus of about 2 TWh in Northern Norway in a mean year. Statnett expects the power balance for the three northernmost counties to stay unchanged until 2015 and to improve slightly towards 2025 (Statnett 2008 #3: 43). All new power generation will improve the power balance in the region further.

4.2.4 Reliability of Power Supply

The electricity delivered must not only be delivered at the right power; it must be of the right quality, i.e. the plant must not be exposed to abrupt changes in power supply. Power supply must be continuous, and should not be subject to voltage dips. The robustness of the power import through the grid had to be evaluated to see if this could be a sound way to supply STII. In this work, it was decided only to look at the frequency of power cuts, as the power quality can be maintained by use of utilities such as condenser banks etc.

Conferring with figure 4.2, the N-1 criterion is satisfied for all line segments except from the one between Balsfjord and Hammerfest. The N-1 criterion expresses the ability of the transmission system to lose a linkage without causing an overload failure elsewhere (Keulenaer 2006). All cuts experienced by the Balsfjord-Hammerfest transmission line will thus affect STII directly. Incidents that lead to a loss of this grid linkage would be the worst case scenario with regards to power supply, in that operation of the LNG plant is impossible without power and that the plant will be shut down.

The consequences of incidents that lead to line loss are most serious from an economical perspective; a line loss is likelier to bring along economical loss than to result in injuries to humans or environmental damage. A line loss should therefore be graded from an economical perspective.

Definitions (Statnett 2008 #2):

- ILE: the amount of energy that would have been delivered to the end user if the power supply was not interrupted.
- Power cuts: incidents with missing or reduced power supply to one or more consumers, where the supply voltage is less than 1 % of contracted voltage level. Power cuts are classified as *prolonged cuts* (>3min) or *short duration cuts* (<3min) and can be either planned or unforeseen.
- Fault: when a component of the transmission system lacks the ability to perform like it is supposed to. A fault does not necessarily lead to a power cut.

The reliability of the power supply describes the availability of power, and is closely connected to the frequency and duration of power cuts.

The trend from early 1990s and onwards to 2005 was that the number of power cut incidents stayed stable, but that the duration of cuts and the amount of ILE was reduced significantly. ILE was about halved in the period (SINTEF 2007 #2). However, these statistical facts do not predict the vulnerability of the grid infrastructure in any way. Underlying causes have not been discussed, and one could for example imagine that there would be a sudden and sharp increase in incidents if the majority of transmission lines exceed their predicted life expectancy simultaneously.

In 2005, SINTEF made a presentation on whether the reliability of power supply on a national basis had improved or not. They found that the three northernmost counties have the greatest portion of ILE (about 40 % of total), indicating that the reliability of power supply is low there compared to the rest of the country. About 75 % of the ILE is caused by interruptions to lines of less than 22 kV. Statistical data for faults and power cuts is available for Norway as a whole, summarized over a wide range of grid voltages. No conclusions could be made with basis in fault and outage data from NVE, and it was suggested that better methods had to be developed to provide knowledge on which control of reliability and vulnerability could be based (SINTEF 2005).

The evaluation of the regularity of power supply has been done many times before, and a methodology of how to do this has been established. NVE recommends that grid companies always keep an updated risk and vulnerability analysis (RIVA). The methodology behind a RIVA analysis can be found in appendix B. This is a straightforward method to identify and continuously monitor vulnerability, and to plan remedial action. The RIVA framework identifies vulnerability and risk in a systematic manner, and helps in conducting risk minimizing measures and planning emergency preparedness. Taking the risk for unwanted incidents into account, the method establishes an overview of whether action must be taken to minimize risk. There are legal requirements for transmission system operators to have such analyses conducted in relation to power supply (Lovdata #1).

It was soon realized that the types of incidents of interest to the STII case, were those that involves a line loss between Balsfjord and Hammerfest. Such line losses would be the consequence of for example extreme weather conditions or the occurrence of several smaller faults simultaneously. For such incidents, Statnett concludes that statistical data is not much worth. Statistical data is applicable for predicting the probability of faults per component, but the loss of a grid linkage is a more complex picture. The connection between different kind of faults and actual power cuts, which are much more seldom, is not clear; it is not explicitly or implicitly available from the available statistical data (Statnett 2008 #2, NVE 2008).

In accordance with the original goal of conducting a simple RIVA, different kinds of components faults that could alone or as part of a series of faults lead to a power cut, were mapped. Possible underlying causes were also listed. The determination of probabilities for each one cause, or combination of different causes, was however found to be comprehensive and uncertain. Because of this and the unclear connection between faults and actual power cuts, it was chosen to use power cut statistics directly to predict the reliability of the power supply to STII, rather than carrying out a RIVA.

Probability of power cuts in the 420 kV line Balsfjord – Hammerfest

The most important grid connection for the power supply to STII is the reinforced 420 kV connection from Balsfjord to Hammerfest. It was therefore of interest to establish predictions of the expected number of power cuts originating in this type of line specifically.

According to Statnett, there are approximately 2500 km of 420 kV lines in the national grid (Statnett 2008 #3: 25-27). The total number of prolonged and short duration power cuts in this grid, from 1998 to 2007, was found in statistics published by Statnett (Statnett 2008 #2). From 1998 to 2007, there were on average 2.9 prolonged outages and 0.6 short duration outages annually, in 420 kV transmission lines in Norway, see table 4.9.

Consequence of fault	*1998-2007 average*
No power cut	78
Short duration cut	0.6
Prolonged cut	2.9

Table 4.9: Consequences of faults in the 420 kV power lines (Statnett 2008 #2)

The new 420 kV connection from Balsfjord to Hammerfest will be about 360 km long (Statnett, no date). Assuming that the probability for cuts is the same for all 420 kV lines in Norway, i.e. not considering age and load history and so forth, the expected value for power cuts per year in the Balsfjord – Hammerfest connection can be estimated as in table 4.10.

Type	*Expected value*
Short duration cut	0.09
Prolonged cut	0.42

Table 4.10: Expected number of power cuts p. a. in a 360 km long 420 kV power line

It is not clear how the probability for cuts depend on the time of year, however, the surroundings usually impose stronger loads on the power system in wintertime. The annual statistics from 1998-2007 tells that cut incidents in the 33 kV - 420 kV grid have shown to be evenly distributed over the year, with a slight top in January.

Only few faults lead to cuts, and the statistically based probabilities for power cuts given in table 4.10 cover all kind of faults and causes. Prolonged power cuts are likely to happen almost every second year, while short duration cuts are likely every tenth year. However, this division is not sufficient to determine the economical consequence for STII. Prolonged cuts can last a few minutes or up to several weeks.

Referring to NVE (2008), the amount of ILE relative to the total delivered power to end user from 1996 to 2007 indicates that power import from the grid is extremely reliable. The ILE to actual delivery ratio nationwide has sunk from about 0.35 per thousand and stabilized at about 0.13 per thousand through the last four years. For Finnmark and Troms, the values are 0.65 and 0.45 per thousand respectively for 2001-2006 (NVE 2008: 32). Taking the mean of the two latter values, as the line from Balsfjord to Hammerfest crosses through both counties, this gives a reliability of power import from the grid of 99.945 %. In other words, power import through the grid will be unavailable for less than 5 hours per year.

What is important for STII is how the reliability of power import through the grid compares to alternative power supply. Values for the reliability of gas turbine fleets in operation were found, ranging from 99.14 to 99.7 percent for LM 6000 gas turbines (GE no date, GE 1995). Harrison et al (2002) used a value of 99.4 % for the reliability of gas turbines relevant for an LNG project in Angola, and this value was adopted to represent the turbines of Train I.

Equipment	***Average reliability***
Gas turbines	99.4%
Power grid	99.945%

Table 4.11: Reliability of power supply

Reliabilities for gas turbines and power import from the grid, i.e. the power supply of Train I and STII respectively, are listed in table 4.11. Power supply from the grid is more reliable than power supply from gas turbines.

Concluding

The most damaging incidents are often triggered by rare events, and fault statistics are thus of limited value. Rare events such as for example extreme and unpredictable weather conditions are difficult to hedge against. It seems like the reliability of power supply to STII can best be predicted by general power cut statistics for the 420 kV national grid. This was found to give 4.2 prolonged and 0.9 short duration power cuts per ten years. With respect to reliability, the STII power supply seems to be superior to that of Train I.

4.2.5 SH share of Grid Reinforcement

The grid reinforcement between Balsfjord and Hammerfest might not be realized without the realization of STII with power supply from the national grid. It is therefore expected that SH must pay a share of this capital expenditure imposed by Statnett. According to SH it is reasonable to assume a SH share of this grid improvement of MUSD 120 (Bomstad and Nordland 2008).

4.3 Heat supply from gas furnaces

4.3.1 Fuel consumption and NO_x emissions

The fuel gas consumption and the NO_x emissions have been provided by SH for a 50 % STII (Bomstad and Nordland 2008). These numbers have been scaled to get numbers for a 70 % STII by assuming a linear relationship between train size and heat demand. The results are summarized in table 4.12.

Fuel consumption and NO_x emissions			***Unit***
Fuel consumption	Fuel gas (50 % STII)	88	MSm^3/year
	Fuel gas (70 % STII)	123	MSm^3/year
NO_x emissions	NO_x Gas furnace (50 % STII)	1.30	kg/hr
	NO_x Gas furnace (70 % STII)	1.82	kg/hr

Table 4.12: Fuel consumption and NO_x emissions for gas furnace

4.3.2 Economic figures for gas furnace

The key expenses for a gas furnace installed and operated at Melkøya were provided by SH (Bomstad and Nordland 2008). The expenses are summarized in table 4.13.

Expenses (2009 NOK)		Unit
Gas price	600,000	NOK/MSm^3
OPEX, gas furnace	1.2	Euro/MWh
CAPEX, gas furnace	11.2	MNOK/MW

Table 4.13: Key expenses for gas furnace

4.4 Offsetting GWP by Wind Power

The purpose of this section is to find the rated wind power which is needed to offset the GWP of the proposed energy system. In addition, all known projects in the vicinity of STII have been screened and the most suitable are summarized in a list. Rough production estimates have also been carried out for each of these projects. The methodology for this section can be found in section 3.4.

4.4.1 GWP of the STII Energy System

GWP by energy source

The first step for calculating the rated wind power was to find the GWP for grid power and heat from gas furnaces. This was done by use of SimaPro LCA software and the Ecoinvent database. A recent SINTEF study has been used to estimate the GWP for wind power, as described in section 3.4.1. SINTEF found that by implementing wind power in the Norwegian grid the CO_2 emissions in continental Europe are reduced with 526 kg per MWh wind power production. The results are summarized in figure 4.3.

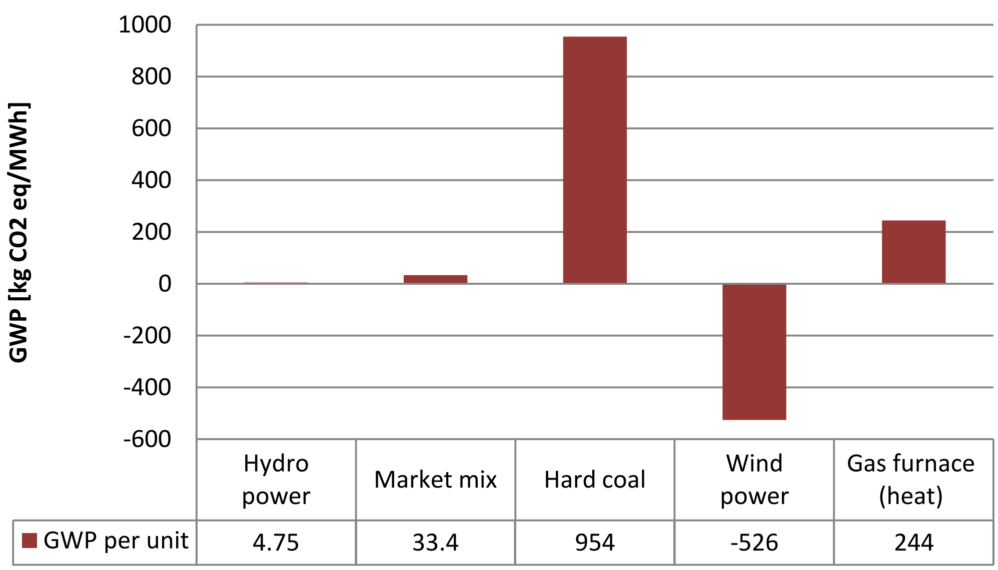
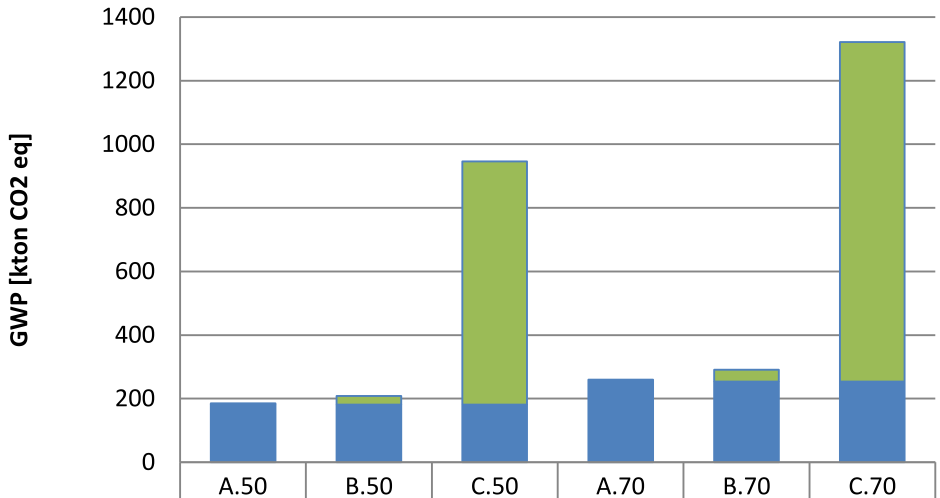


Figure 4.3: GWP by energy source

Total GWP without wind power

The annual GWP for the proposed energy system was found for all scenarios assuming that no wind power was implemented. The numbers were found by multiplying the total heat and power consumption with the corresponding per unit GWP in figure 4.3. The results are reproduced graphically in figure 4.4. The figure shows that the GWP for scenario C.50 and C.70 is remarkably higher than the other scenarios. For reference, the Train I energy system emits approximately 900 kton of CO_2 per year.



	A.50	B.50	C.50	A.70	B.70	C.70
Grid power	3.8	26.8	764.5	5.3	37.4	1,067.2
Gas furnace	181.4	181.4	181.4	253.9	253.9	253.9

Figure 4.4: GWP for energy system without wind power

4.4.2 Share of Wind Power and Rated Wind Power

The share of wind power and the rated wind power were found such that the GWP for the proposed energy system became zero. The results are summarized in table 4.14. The table shows that the share of wind power is similar for Case A and B, while Case C distinguishes itself from the other cases. This goes for both 50 and 70 % STII. The main reason for this is that the grid power in Case C has a significantly higher GWP than in Case A or B, as was shown in figure 4.3.

Scenario	*Share wind power*	*Rated wind power [MW]*	*Wind power production [GWh]*
A.50	43.5%	101	349
B.50	46.4%	107	372
C.50	79.8%	184	639
A.70	43.7%	141	488
B.70	46.5%	150	521
C.70	79.8%	257	893

Table 4.14: Key wind power data by scenario

4.4.5 Recommended Wind Farming Projects

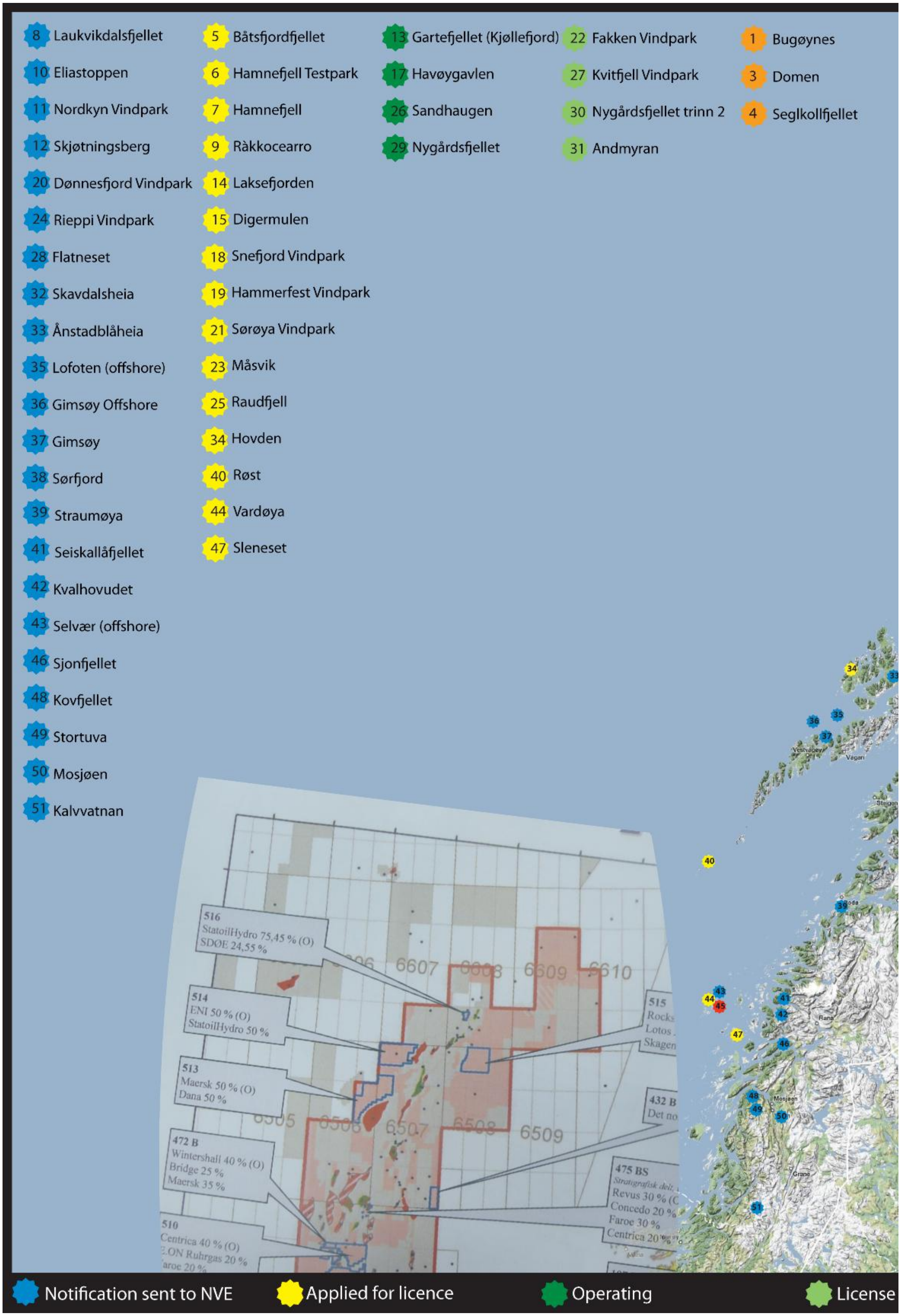
In this section the recommended wind farming projects are presented. The recommendations are the result of the screening described in section 3.4.5. Please confer with that section for a thorough explanation of the screening procedure. All known wind farming projects in the vicinity of STII were considered. An overview of all projects can be seen in the map in figure 4.5.

The list of recommended projects can be found in table 4.15.Use the reference number in the left column to identify the location of the projects on the map in figure 4.5. The projects are ranked by the average score, where three is the highest possible score. There is a production estimate of each project in the right column of the table. The total production potential of these ten projects is approximately 4,300 GWh, considerably higher than the entire power consumption of STII regardless of train size. The annual power consumption for the 70 % STII is expected to be about 1,120 GWh, referring to table 4.5.

Only those projects with a score of two or higher are included in the list. The complete list of the projects can be found in appendix D.

Reference on map	Project Name	Rated Power [MW]	Status	Criterion 1	Criterion 2	Criterion 3	Score	Production Estimate [GWh]
18	**Snefjord**	**160**	Applied for license	3	2	3	**2.7**	**555**
19	**Hammerfest**	**110**	Applied for license	3	2	3	**2.7**	**382**
30	**Nygårdsfjellet (step 2)**	**40**	License granted, not operating	2	3	3	**2.7**	**139**
22	**Fakken**	**60**	License granted, not operating	2	3	3	**2.7**	**208**
27	**Kvitfjell**	**200**	License granted, not operating	2	3	3	**2.7**	**694**
20	**Dønnesfjord**	**100**	Notified	3	1	3	**2.3**	**347**
25	**Raudfjell**	**180**	Applied for license	2	2	3	**2.3**	**624**
31	**Andmyran**	**160**	License granted, not operating	2	3	1	**2.0**	**555**
38	**Sørfjord**	**160**	Notified	2	1	3	**2.0**	**555**
24	**Rieppi**	**63**	Notified	2	1	3	**2.0**	**219**
Total								**4,277**

Table 4.15: Suitable wind farming projects for STII energy system


8 Laukvikdalsfjellet
10 Eliastoppen
11 Nordkyn Vindpark
12 Skjøtningsberg
20 Dønnesfjord Vindpark
24 Rieppi Vindpark
28 Flatneset
32 Skavdalsheia
33 Ånstadblåheia
35 Lofoten (offshore)
36 Gimsøy Offshore
37 Gimsøy
38 Sørfjord
39 Straumøya
41 Seiskallåfjellet
42 Kvalhovudet
43 Selvær (offshore)
46 Sjonfjellet
48 Kovfjellet
49 Stortuva
50 Mosjøen
51 Kalvvatnan
5 Båtsfjordfjellet
6 Hamnefjell Testpark
7 Hamnefjell
9 Ràkkocearro
14 Laksefjorden
15 Digermulen
18 Snefjord Vindpark
19 Hammerfest Vindpark
21 Sørøya Vindpark
23 Måsvik
25 Raudfjell
34 Hovden
40 Røst
44 Vardøya
47 Sleneset
13 Gartefjellet (Kjøllefjord)
17 Havøygavlen
26 Sandhaugen
29 Nygårdsfjellet
22 Fakken Vindpark
27 Kvitfjell Vindpark
30 Nygårdsfjellet trinn 2
31 Andmyran
1 Bugøynes
3 Domen
4 Seglkollfjellet
516
StatoilHydro 75,45 % (O)
SDØE 24,55 %
514
ENI 50 % (O)
StatoilHydro 50 %
513
Maersk 50 % (O)
Dana 50 %
472 B
Wintershall 40 % (O)
Bridge 25 %
Maersk 35 %
6607
6609
6610
6505
6507
6508
6509
Notification sent to NVE
Applied for licence
Operating
License

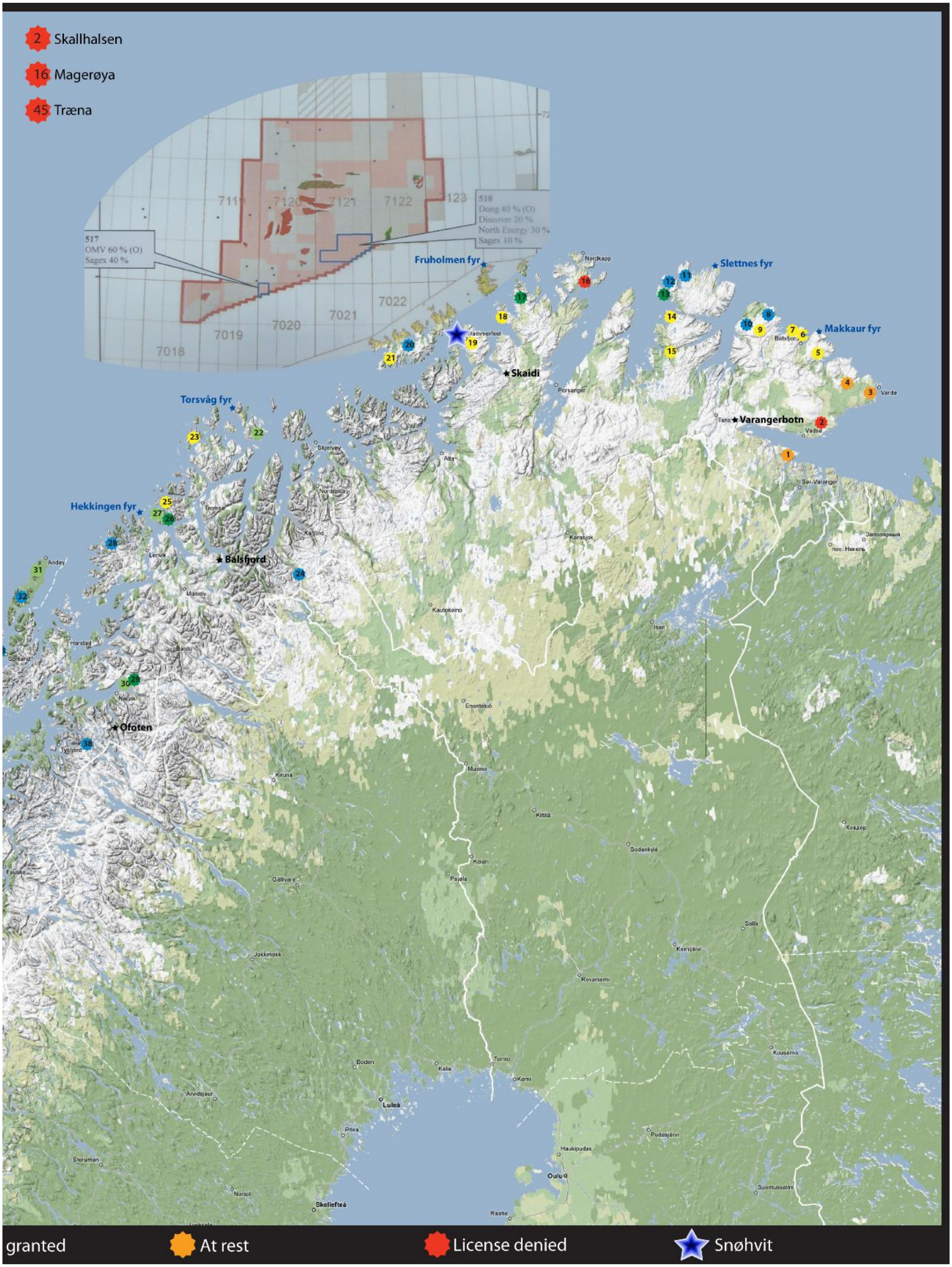


Figure 4.5: Overview of wind farming projects in the vicinity of STII

4.5 Key Figures for the Investment Analysis

This section includes a brief summary of all parameters fed into the investment analysis model. The parameters fed into the model are partly calculated earlier in this report, partly gathered from public sources and partly obtained directly from SH. All of the parameters and their origin have been discussed earlier in the report.

Key figures for the power supply

The most important power figures for both train sizes are summarized in table 4.16. The annual power consumption is calculated based on 330 days of operation per year.

Key power figures			***Unit***
50 % STII	Power demand	101.4	MW_{el}
	Annual power consumption	803.1	GWh
70 % STII	Power demand	141.4	MW_{el}
	Annual power consumption	1,119.9	GWh

Table 4.16: Key power figures for STII

The shares of wind power and rated wind power are summarized for each scenario in table 4.17.

Scenario	***Share wind power***	***Rated wind power [MW]***	***Wind power production [GWh]***
A.50	43.5%	101	349
B.50	46.4%	107	372
C.50	79.8%	184	639
A.70	43.7%	141	488
B.70	46.5%	150	521
C.70	79.8%	257	893

Table 4.17: Key wind power data by scenario

Known expenses and other key economic data for the STII power supply are summarized in table 4.18.

Key economic data	Description		Unit:
Expenses (2009 NOK)	El. price assumption	450	NOK/MWh
	CAPEX, wind farm	13.3	$MNOK/MW_{el}$
	Grid connection of wind farm	1	$MNOK/MW_{el}$
	Operation and maintenance, wind farms	130	NOK/MWh
	Fixed cost, grid connection	129,000	NOK/MW_{el}
	Power cable Balsfjord-Hammerfest, SH share	120	MUSD
Miscellaneous	Current year	2009	
	Start of operation	2016	
	Economic lifetime of project	25	years
	Discount rate	8%	p.a.
	Price inflation	2%	p.a.
	Corporate tax rate	28%	p.a.
	Depreciation rate estimate	10%	p.a.
	Exchange rate NOK/USD (May 1st 2009)	6.55	NOK/USD
	Governmental support (Enova)	-	MNOK/MW

Table 4.18: Key economic data for the STII power supply

Key figures for the heat supply

The most important heat figures for both train sizes are summarized in table 4.19. The annual heat consumption is calculated based on 330 days of operation per year.

Key heat figures			Unit
50 % STII	Heat demand	93.8	MW
	Annual heat consumption	742.9	GWh
70 % STII	Heat demand	131.3	MW
	Annual heat consumption	1,039.9	GWh

Table 4.19: Key heat figures for STII

Known expenses and other key economic data for the STII heat supply are summarized in table 4.20.

Key economic data	*Description*		*Unit:*
Expenses (2009 NOK)	Gas price assumption	600,000	NOK/MSm^3
	Operation and maintenance, gas furnace	1.2	Euro/MWh
	CAPEX, gas furnace	11.2	MNOK/MW
Emission tax	CO_2 tax	460	NOK/kSm^3 NG
	NO_x tax	15.85	NOK/kg NO_x
NG consumption	Fuel gas (50 % STII)	88	MSm^3/year
	Fuel gas (70 % STII)	123	MSm^3/year
NO_x emissions	NO_x Gas furnace (50 % STII)	1.30	kg/hr
	NO_x Gas furnace (70 % STII)	1.82	kg/hr
Miscellaneous	Current year	2009	
	Start of operation	2016	
	Economic lifetime of project	25	years
	Discount rate	8%	p.a.
	Price inflation	2%	p.a.
	Corporate tax rate	28%	p.a.
	Depreciation rate	33.3%	p.a.
	Uplift	7.5%	p.a.
	Special tax rate	50%	p.a.
	Loss carried forward, interest rate	4.1%	p.a.
	Exchange rate NOK/Euro (May 1st 2009)	8.68	NOK/Euro

Table 4.20: Key economic data for the STII heat supply

4.6 Investment Analysis of the STII Energy System

4.6.1 Net Present Cost (NPC)

First the NPC was calculated individually for the heat and power supply. Thereafter the NPC was split into SH share and government share. The offshore tax system is designed such that the government both charges 78 % of the profits and pays 78 % of the expenses. In brief, this implies that SH pays only 22 % of the energy system cost after considering tax effects. The NPC for each of the scenarios can be seen in table 4.21. Note that the NPC is approximately the same for all cases for both STII train sizes. However, the NPC is marginally lower for Case C for both train sizes, i.e. the scenarios with the highest share of wind power.

Net Present Cost (MNOK)	***50 % STII***			***70 % STII***		
Scenario	**A.50**	**B.50**	**C.50**	**A.70**	**B.70**	**C.70**
Power supply	3,990	3,989	3,987	5,343	5,343	5,339
SH share (22 %)	878	878	877	1,176	1,175	1,175
Government share (78 %)	3,112	3,112	3,110	4,168	4,168	4,165
Heat supply	1,671	1,671	1,671	2,338	2,338	2,338
SH share (22 %)	368	368	368	514	514	514
Government share (78 %)	1,303	1,303	1,303	1,824	1,824	1,824
Total	5,660	5,660	5,657	7,682	7,682	7,678
SH share (22 %)	1,245	1,245	1,245	1,690	1,690	1,689
Government share (78 %)	4,415	4,415	4,413	5,992	5,992	5,989

Table 4.21: Net present cost for STII energy system (2009 NOK)

There is a main assumption for these calculations to be realistic. The assumption is that all expenses for the power system are taken on by a related company in the ordinary tax regime. The related company must then be paid by SH such that the expenses and a reasonable rate of return are covered according to the arms length principle[1]. Finally, the expenses paid by SH could thereafter be deducted from the STII income in the offshore tax regime. The reasoning for this is further discussed in section 5.5.1.

4.6.2 Break Even (BE) Power and Heat Prices

The BE power and heat prices are those prices that gave an NPV of zero for the entire STII energy system. These prices were found for each scenario and summarized in table 4.22. Similarly as in section 4.6.1 the BE energy prices were split into a SH share and a government share. Contrary to the NPC, the BE power prices are higher for Case C than for the other cases. The tax system appears to favor the least capital intensive scenarios as the NPC was about equal for all cases for both train sizes. The BE heat prices were found to be the same for all scenarios because the expenses scaled linearly.

[1] The arms length principle is commonly applied to commercial and financial transactions between related companies. It says that transactions should be valued as if they had been carried out between unrelated parties, each of them acting in his own best interest (OECD).

Break Even Price (NOK/MWh)	*50 % STII*			*70 % STII*		
Scenario	**A.50**	**B.50**	**C.50**	**A.70**	**B.70**	**C.70**
Power	570.05	571.24	585.04	545.86	547.02	560.78
SH share (22 %)	125.41	125.67	128.71	120.09	120.34	123.37
Government share (78 %)	444.64	445.57	456.33	425.77	426.68	437.41
Heat	282,87	282,87	282,87	282,87	282,87	282,87
SH share (22 %)	62.23	62.23	62.23	62.23	62.23	62.23
Government share (78 %)	220.64	220.64	220.64	220.64	220.64	220.64

Table 4.22: Break even power and heat prices (2009 NOK)

It should be noted that the BE power prices are noticeably higher for 50 % STII than for 70 % STII. This is mainly due to the SH share of the grid improvement between Balsfjord and Hammerfest, which is fixed and not a function of the train size. The BE power prices were recalculated without this share to see how the BE power prices compare between train sizes beside from this expense. In addition, the BE power prices were calculated without wind power in order to see how much extra SH has to pay for implementing wind power in the energy system. Lastly, the BE power prices were recalculated with neither wind power nor the SH share of the grid improvement. The resulting BE power prices with each of these three modifications are shown in table 4.23. The decrease from the baseline are calculated in percent and highlighted with orange in the same table.

Break Even Price (NOK/MWh)	*50 % STII*			*70 % STII*		
Scenario	**A.50**	**B.50**	**C.50**	**A.70**	**B.70**	**C.70**
Power, without SH share of grid improvement	484.34	485.46	499.26	484.34	485.50	499.26
SH share (22 %)	106.55	106.80	109.84	106.55	106.81	109.84
Government share (78 %)	377.79	378.66	389.42	377.79	378.69	389.42
Percent decrease from baseline	15.04%	15.02%	14.66%	11.27%	11.25%	10.97%
Power, 0 % wind power	552.07	552.07	552.07	527.81	527.81	527.81
SH share (22 %)	121.46	121.46	121.46	116.12	116.12	116.12
Government share (78 %)	430.61	430.61	430.61	411.69	411.69	411.69
Percent decrease from baseline	3.15%	3.36%	5.64%	3.31%	3.51%	5.88%
Power, without SH share of grid improvement and 0 % wind power	466.29	466.29	466.29	466.29	466.29	466.29
SH share (22 %)	102.58	102.58	102.58	102.58	102.58	102.58
Government share (78 %)	363.71	363.71	363.71	363.71	363.71	363.71
Percent decrease from baseline	18.20%	18.37%	20.30%	14.58%	14.76%	16.85%

Table 4.23: Alternative break even power prices (2009 NOK)

Note that the BE power price without wind power and the SH share of the grid improvement is equal for all scenarios, i.e. NOK 466 per MWh. If the GWP of the STII energy system is to be offset by development of wind power, the BE electricity prices would increase to 484-489 NOK/MWh, depending on train size and the interpretation of marginal power consumption. Moreover, if SH also must pay a share of the grid reinforcement necessary to supply STII, in addition to developing wind power, the BE electricity price will increase to 570-585 NOK/MWh for the 50 % STII and 546-561 NOK/MWh for the 70 % STII. Lastly, SH share of grid reinforcements but no wind power to offset the GWP will give a BE power price of 552 NOK/MWh for the 50 % STII and 528 NOK/MWh for the 70 % STII.

4.6.3 Sensitivity Analysis

The baseline for the sensitivity analysis was the investment model where the net present value (NPV) was equal to zero, i.e. with the income set equal to the BE heat and power prices multiplied with the heat and power consumption respectively. The results are presented graphically to indicate as intuitively as possible which parameters are the most critical in the investment analysis.

Power supply for 50 % STII

The first sensitivity analysis was performed for all cases based on the power demand imposed by the 50 % STII. The results are shown in figure 4.6. The parameters that were changed are along the y-axis, while the new NPV for each of these can be read from the x-axis. A positive NPV indicates an improvement of the economic performance and vice versa.

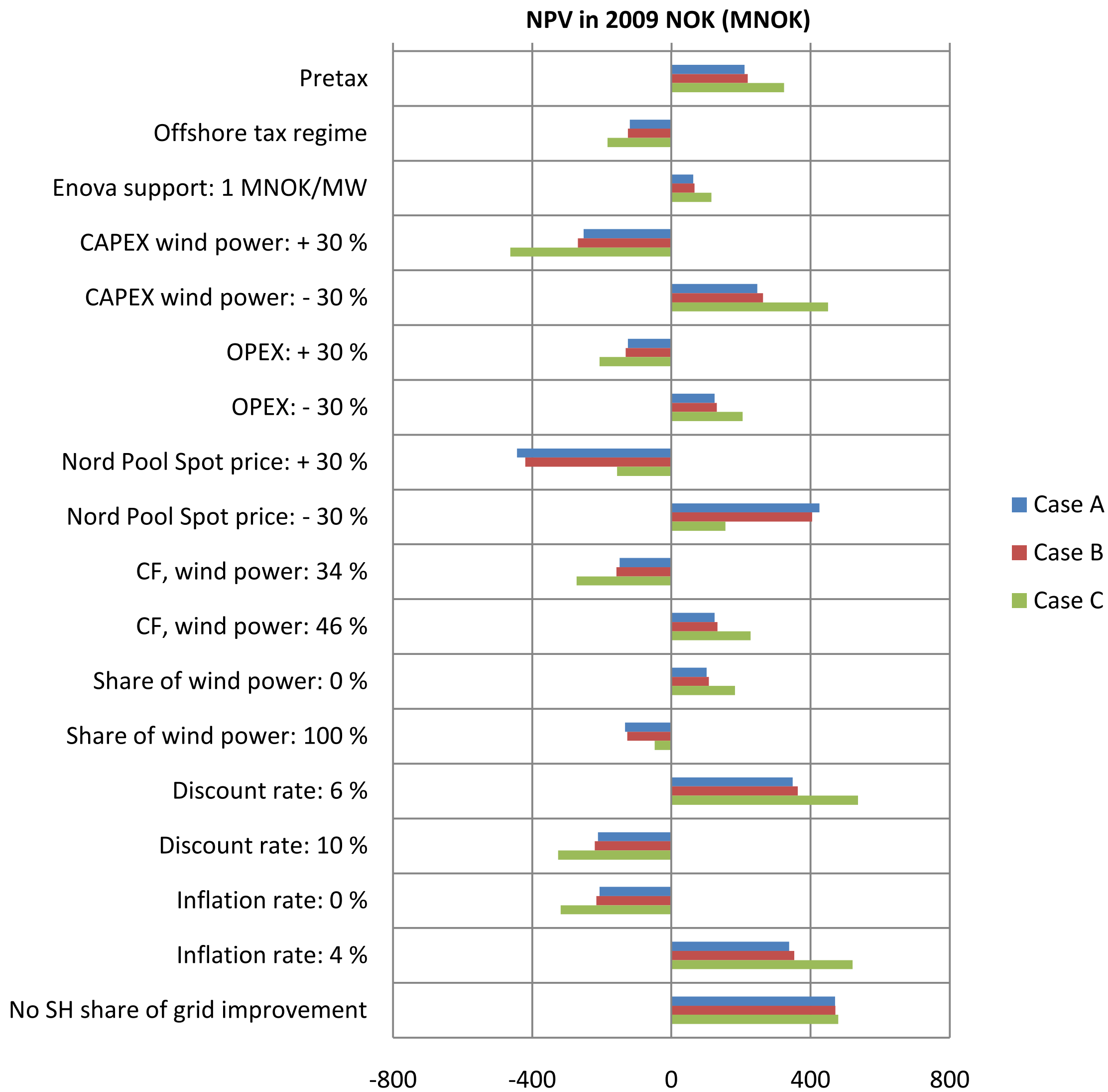


Figure 4.6: Sensitivity analysis for the power supply, 50 % STII (2009 NOK)

The first observation form the sensitivity analysis is that the NPV is higher before considering tax effects, and the NPV is lower if the power supply were to be defined in the offshore tax system. It is of interest to note that Case C is less sensitive to changes in the Nord Pool Spot price and more sensitive to changes in the CAPEX and OPEX as compared with Case A and B. Also note that in general the energy system is more sensitive to changes in CAPEX than OPEX. Governmental support through Enova of MNOK 1 per MW rated wind power just barely increases the NPV of the energy system. The analysis shows that if SH can avoid their share of the grid improvement between Balsfjord and Hammerfest the NPV increases significantly for all cases. Lastly, note that both the choice of interest rate and inflation rate influences the NPV significantly.

Power supply for 70 % STII

The second sensitivity analysis was performed for all cases based on the power demand imposed by the 70 % STII. The results are shown in figure 4.7.

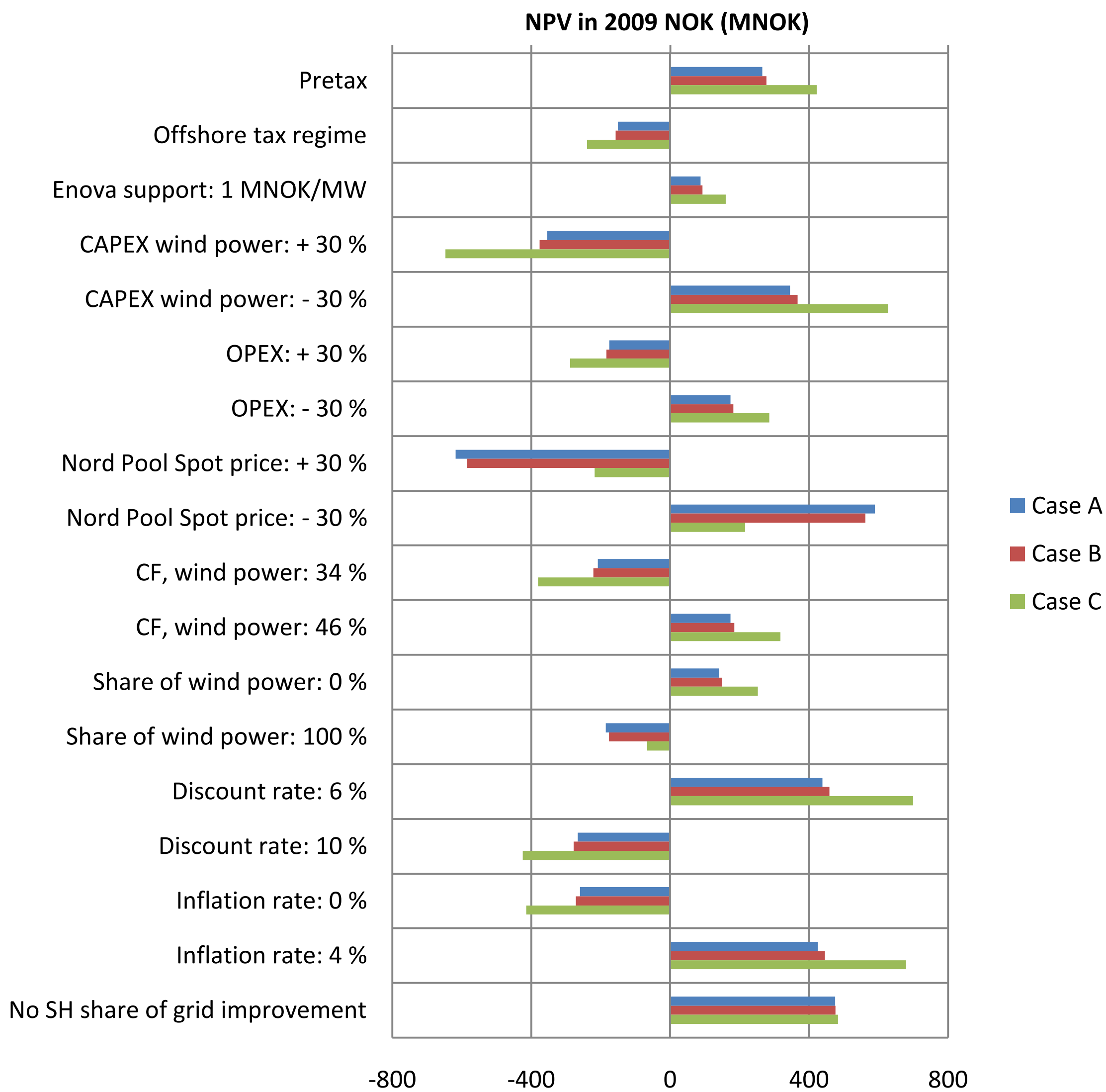


Figure 4.7: Sensitivity analysis for the power supply, 70 % STII (2009 NOK)

The general observations for 50 % STII are also valid as for 70 % STII. The same changes in the input for 70 % STII gave larger effects in the output as compared with 50 % STII because the investments are larger with the former train size. The exception is if SH can avoid their share of the grid improvement. This is because the SH share is a lump sum and does not depend on train size.

Heat supply for STII

The third sensitivity analysis was performed based on the heat demand imposed by both train sizes. The results are shown in figure 4.8.

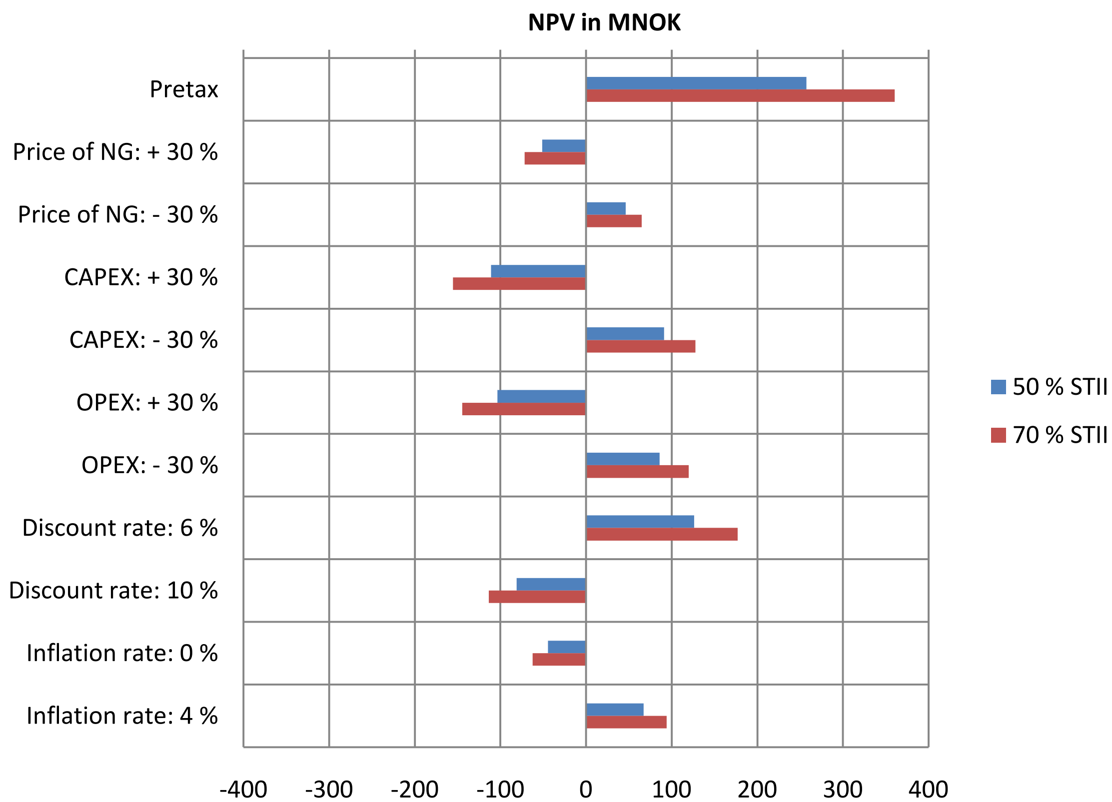


Figure 4.8: Sensitivity analysis for the heat supply (2009 NOK)

The first observation is that the post-tax NPV is significantly lower the pretax NPV. This indicates how much the NPV is lowered due to tax payments in the offshore tax regime. Variations in the natural gas (NG) price are less important than changes in CAPEX and OPEX, while changes in CAPEX and OPEX seem to be equally important. Lastly, note that both the choice of interest rate and inflation rate influences the NPV significantly.

CHAPTER 5: DISCUSSION

5.1 STII Energy Demand

The determination of power and heat demand for STII was necessary in order to provide input to the investment analysis via the GWP analysis. The amounts of heat and power that must be supplied have direct influence on the GWP of the STII energy system, and are thus cardinal parameters in the determination of the energy system cost.

5.1.1 Combination of Data Sets

The heat and power demand for STII was quantified also in the project thesis preceding this master thesis. In the project thesis these estimates were based solely on company provided information. Due to inconsistencies in this information it was a goal in this work to develop better energy estimates. The STII energy estimates developed in this master thesis are based both on simulations and data provided by the company.

It would have been preferable to base the energy estimates fully on own process simulations. However, with advice from the supervisor it was decided to omit parts of the LNG process plant from the simulations and rather focus on selected parts. This was mainly due to a high level of complexity and an extensive scope. Time also had to be spent on becoming familiar with the simulation software, HYSYS. The liquefaction plant, with the integrated removal of heavy hydrocarbons, was simulated. The resulting power consumption proved to be significantly lower than that given in information from SH. This deviation was almost eliminated through added contingency margins.

Difficulties with simulations were expected in connection with the simulation of distillation columns in particular, and were also experienced in form of the HHC removal column that is integrated in the liquefaction process. At Snøhvit, heat is mainly supplied in boilers in connection with processing columns; endothermic stripping of CO_2 from amine-based solvent constitute 42 % of the total energy demand and fractionation 18 %. In accordance with advice from our supervisor, simulation of distillation columns was for the most part avoided as this has been attended with difficulties in former student works. The key heat figures were based solely on scaling of train I figures.

The train I power figures were established from rated power of installed components at Melkøya. It was assumed that components in continuous operation always run at rated power, and that components in intermittent operation run at 40 % of rated power, continuously. This means that the Train I figures are probably too high; components have been designed to cover peak load, and rated powers moreover include various types of margins to take contingency into account. The liquefaction plant with the cooling compressors constitute 67 % of the total Train I demand and was therefore chosen for simulation in order to gain a better estimate of the power requirements. A contingency and loss factor of 15 % was added on top of the simulation results. The total STII power estimates were found by combining the simulation results with the residual Train I figures adjusted for train size. Due to wear and tear, an ageing effect of 2 % was added on top of the STII power estimate to account for reduced efficiency with ageing of the plant.

5.1.2 STII Energy Figures

The final energy figures are reproduced in table 5.1 and 5.2. These are used as input to both the GWP analysis and the investment analysis.

Key power figures			***Unit***
50 % STII	Power demand	101.4	MW_{el}
	Annual power consumption	803.1	GWh
70 % STII	Power demand	141.4	MW_{el}
	Annual power consumption	1,119.9	GWh

Table 5.1: Key power figures for STII

Key heat figures			***Unit***
50 % STII	Heat demand	93.8	MW_{el}
	Annual heat consumption	742.9	GWh
70 % STII	Heat demand	131.3	MW_{el}
	Annual heat consumption	1,039.9	GWh

Table 5.2: Key heat figures for STII

5.1.3 Recommendations for Further Work

This master thesis touches a variety of topics. Many of these could advantageously have been studied more in-depth. Most importantly, it would have been preferable to simulate the whole LNG process. The combination of numbers provided by the company with results from performed simulations to form a whole is somewhat not satisfactory. Underlying assumptions are not known and might be different for the combined data sets. The challenges with performing such simulations, as pointed out by the supervisor, would require this task to be carried out separately as stand-alone work, and not have other work depend on early output.

Moreover, there was not time to investigate, by simulations, the possible heat and power reductions that could be achieved through changes to the process configuration. Some were suggested in this work, for example shifting to upstream instead of integrated removal of heavy hydrocarbons. It would have been interesting to quantify the influence of such modifications on the heat and power figures.

An obvious way of reducing the power demand would be to utilize flash gas as fuel, and thereby avoid the power consumption for the cryogenic separation of nitrogen and methane. The heat available to a heat transfer fluid from combustion of flash gas is given in table 5.3. It exceeds the STII heat demand by approximately 60 %, and it was therefore concluded that an NRU is needed and imposes a power demand on STII, as in Train I.

Heat energy			***Unit***
50 % STII	Energy in flash gas	150.4	MW
	STII demand	93.8	MW
70 % STII	Energy in flash gas	210.6	MW
	STII demand	131.3	MW

Table 5.3: Thermal content of flash gas stream vs. STII heat demand

A redesign of the power and heat system at Melkøya, including Train I, could render the utilization of flash gas and thereby energy savings possible. This has not been within the scope of this work, but could form the basis of an interesting future assignment.

5.2 Regularity of Power Import

5.2.1 Tripartite Security of Supply

To have security of supply is to have available transmission capacity, a positive power balance and a reliable power transmission system.

The process for reinforcement of the grid in Northern Norway has recently gained momentum. Norway has accepted that EU’s Renewable Energy Directive (RED) also applies to Norway through the European Economic Area. According to NVE the share of renewable energy in Norway’s energy mix is already 58 %, but if Norway is to increase this share in line with the EU members, it would mean that 72 % should come from renewable sources by 2020. With no increase in the consumption, this would entail new renewable production of 32 TWh. *An application license for the new Balsfjord-Hammerfest 420 kV line was sent to NVE in May 2009, and the line is scheduled for commissioning in 2016 (Statnett). The grid reinforcement up to Hammerfest allows for a better utilization of renewable wind resources, and it facilitates a more sustainable development of petroleum activities in Northern Norway.*

Statnett found that the mean year power surplus of about 2 TWh for Nordland, Troms and Finnmark is expected to stay unchanged or improve slightly towards 2025. This strengthens the security of supply for a STII.

5.2.2 Reliability Assessment

It is the responsibility of the Transmission System Operator (TSO) to provide reliable transmission services. Thus it is also the responsibility of the TSO to keep an updated risk and vulnerability analysis for these services in order to identify vulnerability and plan remedial action, maintenance routines and emergency preparedness. Contracted energy delivery that is not delivered will have to be compensated by the TSO.

The reliability of power import from the grid was looked into by studying data sets from NVE and Statnett. Data have only been reported for the last few years, and most of it is neither split by grid voltage nor by geography. Statistical data for 420 kV lines from 1998-2007 indicate that STII is likely to experience power cuts each lasting for more than 3 minutes 0.42 times annually. This implies prolonged power cuts less than every second year. Shorter power cuts are likely to occur less than once per ten years, see table 5.4.

Type	*Expected value*
Short duration cut	0.09
Prolonged cut	0.42

Table 5.4: Expected value for power cuts in the Balsfjord-Hammerfest power line

Referring to NVE, the amount of ILE relative to the total delivered power to end user from 1996 to 2007 indicates that power import from the grid is extremely reliable. The ILE to actual delivery ratio nationwide has sunk from about 0.35 per thousand and stabilized at about 0.13 per thousand through the last four years. For Finnmark and Troms, the values are 0.65 and 0.45 per thousand respectively for 2001-2006. Taking the mean of the two latter values, as the line from Balsfjord to Hammerfest crosses through both counties, this gives a reliability of power import from the grid of 99.945 %. Assuming these numbers are also representative over the time span of STII, power import through the grid will be unavailable less than 5 hours per year.

5.2.3 Superior to Train I Power Supply

What is important for STII is how the reliability of power import through the grid compares to alternative power supply. According to GE, the reliability of the LM 6000 gas turbines in operation at Train I range from 99.1 to 99.7 %. Harrison et al (2002) used a value of 99.4 % for the reliability of gas turbines relevant for an LNG project in Angola, and this value was adopted to represent the turbines of Train I. *The reliabilities for gas turbines and power import from the grid are listed in table 5.5 Power supply from the grid is more reliable than power supply from gas turbines.*

Equipment	*Average reliability*
Gas turbines	99.4%
Power grid	99.945%

Table 5.5: Reliability of power supply

Power cuts due to gas turbine failure can last up to about 52.5 hours in total, and the reliability of power import from the grid will still be higher than that of gas turbines. Assuming that power cuts in relation to STII only origin from the national grid linkage from Balsfjord to Hammerfest, it is expected that STII will experience 0.42 prolonged power cuts per annum, referring to table 5.4. This means that each power cut can last up to 125 hours on average, i.e. more than 5 days, and the STII power supply will still be superior to that of train I in terms of reliability. In 2007, none of the three power cuts in the 420 kV national grid lasted more than 2 hours according to NVE. Longer cuts are only usual for extreme cases, such as line breakdowns due to extreme weather, where lasting storms might hinder the repair or that damage happen in inaccessible locations.

5.2.4 Recommendations for Further Work

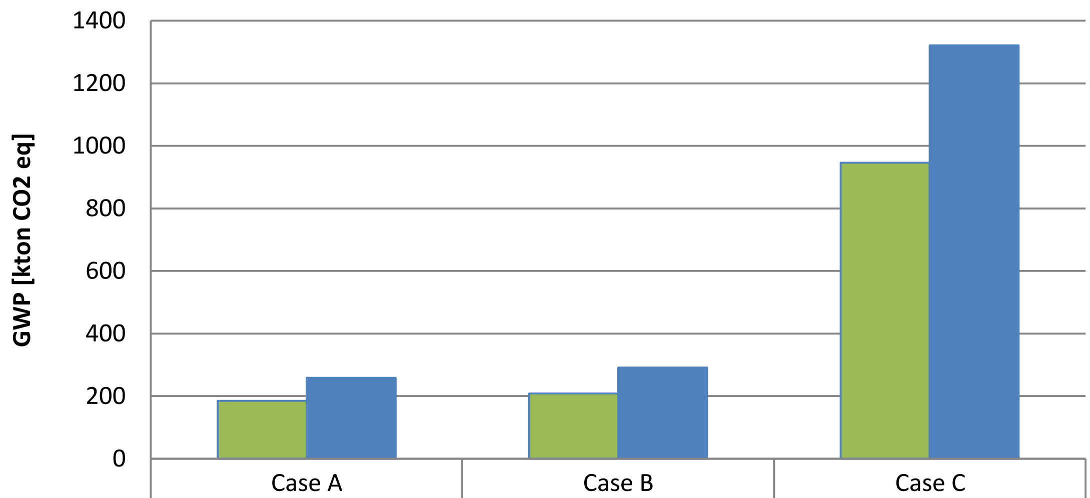
It would be beneficial to have the reliability of power import investigated as stand-alone research. This could include a detailed risk and vulnerability analysis (RIVA), to make possible the identification of hazard and planning of action to improve the reliability of power import to STII. Such work is not the responsibility of an end user, such as SH. It should involve professionals from power companies. The work done so far has only showed that power import from the grid is more reliable than power supply from gas turbines. It has not been investigated how the LNG plant will tackle power cuts or voltage dips of varying duration. Further work should for example try and quantify the economic impact of such incidents on the LNG plant.

5.3 GWP Analysis

5.3.1 GWP Neutral Energy System

An important part of this study has been to quantify the GWP of the different energy sources taking part in the STII energy system. In a recent study SINTEF found that introduction of wind power in the Norwegian power system replaces energy production from fossil fuels in other countries and therefore has a negative GWP. These GWP calculations are conservative as the SINTEF report only considers direct CO_2 emissions from combustion of fossil fuels and not the entire GWP over the lifetime of the power plant. Using the SINTEF methodology, namely that wind power has negative emissions since it reduces less clean energy generation elsewhere, the benefit of introducing wind power in the Norwegian grid would be even higher if the entire GWP was considered. The GWP of the imported grid power and the gas furnace was obtained by use of SimaPro and the Ecoinvent database. These tools give reliable results based on historical data and are widely used, among others by the LCA lab at NTNU.

This paper has mapped the GWP with different viewpoints on the marginal power, but no standpoint has been made on which of the viewpoints should prevail over the others. Three different cases were chosen to illustrate how the results would vary with the different viewpoints. Case A considered the power as environmentally friendly hydro power, Case B as a Nord Pool market mix and Case C as coal power from otherwise idle coal power plants. The GWP without wind power is significantly higher for Case C for both train sizes. This can be seen in figure 5.1.



	Case A	Case B	Case C
50 % STII	185.2	208.2	945.9
70 % STII	259.2	291.3	1,321.1

Figure 5.1: Total GWP for the STII energy system without wind power

Earlier in the report it has been suggested to implement wind power into the STII energy system such that the STII energy system GWP becomes zero. It is uncertain whether it is necessary from a legislation point of view with a GWP of zero. However, with a GWP neutral energy system SH both takes social responsibility regarding climate change and positions itself as an environmentally friendly oil and gas company. This in turn makes it more likely with governmental approval of the STII development and opens doors for doing more business in the future.

5.3.2 GWP Offset by Wind Power

A wind farming capacity factor (CF) of 39.6 % has been used as a baseline throughout this report. This was found to be a representative CF in the vicinity of STII in the project thesis preceding this master thesis. As discussed in section 3.4.3 the average CF in Norway is approximately 34 %, while 46 % can be achieved at optimal sites. The chosen CF might therefore be somewhat optimistic, but still within realistic limits. A lower CF would have led to a higher rated wind power in all scenarios. As a consequence this would affect both the input and the output of the investment analysis.

The share of wind power in the different scenarios and thereby the rated wind power was calculated based on the GWP analysis discussed above. The share of wind power and the rated wind power was found such that the energy system became GWP neutral in each scenario. The results from this analysis are shown in table 5.6. The table shows that the rated wind power ranges from about 100 to 184 MW_{el} for 50 % STII depending on how the marginal power is considered. The rated wind power for 70 % STII ranges from about 140 to 257 MW_{el} correspondingly.

Scenario	*Share wind power*	*Rated wind power [MW]*	*Wind power production [GWh]*
A.50	43.5%	101	349
B.50	46.4%	107	372
C.50	79.8%	184	639
A.70	43.7%	141	488
B.70	46.5%	150	521
C.70	79.8%	257	893

Table 5.6: Key wind power data by scenario

Ten wind farming projects were recommended in section 4.4.5, based on three criteria; location, maturity in the concession process with NVE and the grid situation. Both the first and the last criterion directly or indirectly consider the grid capacity in the region. This implies that the grid capacity is a very decisive factor for the screening of the wind farming projects. However, by locating the wind farms nearby Melkøya one also contributes to increase the security of supply to STII. The total production potential of these ten projects is approximately 4,300 GWh, considerably higher than the entire power consumption of STII regardless of train size. The annual power consumption for the 70 % STII is expected to be about 1,120 GWh.

The central grid has been analyzed and with the future improvements there are no bottlenecks for introducing the wind power suggested in this paper. The scenario with the most wind power, C.70, entails installation of 257 MW rated wind power. Statnett has calculated that the capacity for new wind power generation in Finnmark will be about 500 MW with the new 420 kV transmission line to Hammerfest. The capacity of today for new wind power is 120 MW.

With new power take-offs in Finnmark, such as represented by the Sydvaranger Gruve AS, the Goliat project and STII, the potential for wind power increases. This is because much of the power will be utilized locally. A rough estimate of this increase would be that for each MW new power take-off, one makes place for 2 MW of new wind generation. This has to do with the variation in wind generation over the year, and its correlation to hydro power production.

Although calculations must be performed based on a detailed grid, including all new grid lines and all new producers and consumers, to achieve good figures on the capacity for power supply and the capacity for increased wind power penetration, one can conclude that the capacity will be sufficient to supply STII, either by power generated by new production in Finnmark or exported from further south.

5.3.4 Recommendations for Further Work

As discussed above the GWP calculations are conservative as SINTEF only considered the direct CO_2 emissions that are avoided by introducing wind power in the Norwegian grid, not the entire GWP. Further work should recalculate these impacts with the same methodology as SINTEF but take into account the entire GWP. With more realistic data one can expect that the share of wind power needed to design a GWP neutral STII energy system would be lower than what is found in this paper.

A more thorough screening of wind farming projects should be done before a final choice of projects is made. Radar facilities of the Norwegian Armed Forces, environmental impacts, reindeer husbandry and tourism are criteria that should be considered in a more thorough screening. These criteria have not been included in the screening in this report because this kind of information is not readily known for more than a few of the projects.

5.4 Investment Analysis

The results from the investment analysis are uncertain because the investments are a many years ahead in time and difficult to estimate exactly. Most of the expenses in this report are based on numbers from public reports. The remaining expenses are provided by SH. The single parameter involving most uncertainty is the SH share of the grid improvement between Balsfjord and Hammerfest.

5.4.1 Fiscal Framework for the Power Supply

All power supply expenses are assumed to be taken on in the ordinary tax regime by an associated company, hereafter referred to as *Snøhvit Power*. Snøhvit Power is currently not an existing company and must be established if needed.

It is assumed that SH makes continuous payments to Snøhvit Power for the power delivered to STII. Snøhvit Power must be paid by SH such that the expenses and a reasonable rate of return (8 %) are covered according to the arms length principle[2]. In the perspective of achieving a GWP neutral energy system and thereby also avoiding the cost of CO2 quotas, paying a higher rate than the market power price is defendable within terms of the arms length principle. By using this approach the power supply payments are transferred from the ordinary tax regime to the offshore tax regime. This approach is reasonable as the power from the grid and the wind farms should have the same fiscal framework as any other energy system, e.g. the Train I energy system (combined heat and power plant).

As Snøhvit Power is paid according to their actual expenses by SH, SH's expenses should be deductible from the STII income in the offshore tax regime as any other OPEX. The transfer of the expenses from the ordinary to the offshore tax regime means that the governmental share of the expenses is 78 % instead of 28 %. The governmental share of the expenses is equal to the marginal tax rate due to the deduction of the expenses from the STII income.

As an alternative to establishing Snøhvit Power, one can imagine that SH pays an independent company with expertise in wind power to take on the responsibility to develop wind farms. The rated power should still be equal to what is suggested in this paper. The rationale for doing this is that wind power is outside the core business of SH, namely upstream oil and gas operations. It has not been calculated how much it would be reasonable for SH to pay this company, but it is assumed to be similar to the payments to Snøhvit Power discussed above.

[2] The arms length principle is commonly applied to commercial and financial transactions between related companies. It says that transactions should be valued as if they had been carried out between unrelated parties, each of them acting in his own best interest (OECD).

5.4.2 Net Present Cost (NPC)

The NPC was calculated for each of the six scenarios. The NPC was found to be approximately identical for all cases and thereby independent of the share of wind power in the energy system. However, the NPC is calculated without considering any tax payments as no tax is paid without income in the investment model. In order to find the break even energy prices income is added to the model, and thereby the tax payments are taken into account. To a large extent the tax payments explain the difference between the NPC calculations and the break even energy prices.

5.4.3 Break Even (BE) Energy Prices

The BE power price was found to be approximately the same for all cases, but somewhat higher for Case C. The difference was larger between the train sizes as the BE power prices proved to be higher for 50 % than 70 % STII. This is mainly due to the SH share of the grid improvement between Balsfjord and Hammerfest which is independent of train size. The SH share is not fixed but rather suggested by Statnett, the TSO, which implies that SH might be exempt from this share. Without the SH share of the grid improvement the BE power prices was found to decrease about 15 % for the 50 % STII and about 11 % for the 70 % STII. The decrease was found to be about the same for all cases for each train size. In comparison, if the wind power was completely left out of the STII energy system the BE power price would decrease by 6 % or less for all scenarios. Finally, without the SH share of the grid improvement and assuming no wind power in the energy system the BE power prices were found to decrease with 18-20 % for 50 % STII and 15-17 % for 70 % STII. The results from this analysis are summarized in table 5.7.

Description \ Scenario	***A.50***	***B.50***	***C.50***	***A.70***	***B.70***	***C.70***
BE power price (baseline) (NOK/MWh)	**570.05**	**571.24**	**585.04**	**545.86**	**547.02**	**560.78**
Percent decrease from baseline						
No SH share of grid	15.04%	15.02%	14.66%	11.27%	11.25%	10.97%
0 % wind power	3.15%	3.36%	5.64%	3.31%	3.51%	5.88%
No SH share of grid & 0 % wind power	18.20%	18.37%	20.30%	14.58%	14.76%	16.85%

Table 5.7: Possible reductions in the break even power prices (2009 NOK)

Even though the BE power prices proved to be higher with wind power SH might actually benefit economically from having a GWP neutral energy system. This is because a GWP neutral energy system is assumed exempt from buying CO_2 quotas as the CO_2 emissions are offset already. The additional cost of implementing wind power in the energy system has not been compared with the cost of buying CO_2 quotas.

Another benefit of the proposed energy system is that SH avoids the risks and expenses of taking on the implementation of carbon capture and storage (CCS). The Norwegian government has stated that no more gas fired power plants shall be built in Norway without CCS. CCS is a very immature technology and no facilities are currently in operation on the scale that would have been required at STII. The additional expenses for wind power in the proposed energy system might be preferable to the increased risk and the additional expenses associated with CCS.

The BE heat price for all scenarios was found to be NOK 283 per MWh (2009 NOK).

5.4.4 Sensitivity Analysis

The purpose with the sensitivity analysis was to identify the most decisive parameters in the investment analysis. This was done by changing one parameter at a time; most parameters were changed with ± 30 % and some within more individual, reasonable limits. The impact was measured in form of change in net present value (NPV). Refer to section 4.6.3 for a visual representation of the sensitivity analysis.

General remarks

The energy system proved to be more vulnerable to changes in the CAPEX than in the OPEX.

Power trade and electricity price

The sensitivity analysis indicated that the power supply was less vulnerable to fluctuations in the Nord Pool Spot price with a high share of wind power. As it is very difficult to estimate the long term Nord Pool Spot price this implies that a high share of wind power could make the power price more predictable.

It is assumed that the wind farms sells power to the Nord Pool Spot market in periods of excess wind power production and buys it back in periods of low wind power production. Over time this trade is assumed to take place without any financial gains or losses. This is reasonable as the volume of power bought from the spot market is equal to the volume sold to the spot market. In general the wind is stronger in the winter than in the summer. Spot market prices have historically been higher in the winter due to a higher power demand, among others for heating, and this indicates a financial gain from trade with the Nord Pool Spot market. However, this must be analyzed more thoroughly as other factors than season will influence this trade.

Gas price

The natural gas price was set at NOK .60 per standard cubic meter (Sm^3) after a dialogue with SH. This might seem arbitrary as it is lower than the market value and higher than the tail gas value. For these reasons some might say it is too low and others that it is too high. However, the sensitivity analysis shows that the natural gas price is one of the least vulnerable parameters with a change of ± 30 %. A larger change of the natural gas price is not unlikely because several approaches can be used to find a reasonable price of the natural gas. A larger change may make the natural gas price one of the most important parameters in the investment analysis.

Amount of wind power

The baseline estimate assumed a capacity factor (CF) of 39.6 %. As discussed above the average CF for wind farming in Norway is about 34 %, while 46 % can be achieved at optimal sites. Changes within those limits did not influence the power system NPV significantly for Case A and B, but somewhat more for Case C as the share of wind power is higher.

Compared to the other parameters in the sensitivity analysis a change in the share of wind power did not influence the energy system NVP significantly. The wind power share ranged between 0 and 100 % in the sensitivity analysis, resulting only in small movements in the energy system NPV. This might be interpreted as an inexpensive investment in a better reputation among politicians and the general public. A share of 100 % wind power decreased the NPV only slightly compared to reasonable changes in other parameters of the sensitivity analysis, but could give SH a considerable boost in reputation. This effect is not easily quantifiable, but being known as a developer of sustainable business can be expected to open new business opportunities elsewhere. On the one hand, it must be noted that this opportunity is very sensitive to the CAPEX of wind power. On the other hand, a high share of wind power is also a way of hedging against increase in the market price for electricity, which is not expected to decrease.

Discount rate

Changes in the discount rate from the 8 % baseline influenced the energy system NPV significantly. A discount rate of 6 % gives a higher NPV, while a discount rate of 10 % gives a lower NPV. One factor that contributes to reinforce the magnitude of this phenomenon is that the start-up of STII is many years ahead in time and the NPV is discounted back to the present year. Nevertheless, a discount rate of 8 % is recognized as representative for a screening of projects by SH as it gives a good indication of the project economy at an early stage.

Inflation rate

The inflation rate also proved to be an important parameter in the sensitivity analysis. The baseline estimate was set at 2 %, while 0 and 4 % was used as a lower and higher range in the sensitivity analysis. An inflation rate of 0 % lowered the energy system NPV for all projects, but most for Case C as it has a higher CAPEX. Correspondingly, an inflation rate of 4 % increased the NPV significantly for all cases.

Heat supply

The pretax NPV was the single most important parameter in the sensitivity analysis of the heat supply. The result indicates that the pretax value of the heat supply would be significantly higher if the investment was not subject to tax payments. The large difference is due to the marginal tax rate of 78 % in the offshore tax system. However, as the expenses are deducted from the STII income the government indirectly takes a 78 % share of the heat system and SH is better off by having the heat supply in the offshore tax system.

5.4.5 Recommendations for Further Work

Even though the BE power prices proved to be higher with wind power SH might actually benefit economically from having a GWP neutral energy system. This is because a GWP neutral energy system is assumed to be exempt from buying CO_2 quotas as the CO_2 emissions are offset already. The additional cost of implementing wind power in the energy system has not been compared with the cost of buying CO_2 quotas. This is however an interesting comparison that should be done if the work with the proposed energy system is carried forward.

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CHAPTER 6: CONCLUSION

It has been proposed to supply heat and power to Snøhvit Train II (STII) from onsite heat generation based on natural gas and power import from the power grid. Greenhouse gas emissions from the combustion of natural gas in furnaces, without carbon capture and storage, make considerable contribution to the global warming potential (GWP) of this energy system. Depending on the interpretation of marginal power consumption, also the power import contributes to increase the GWP. A recent SINTEF report claimed that European CO_2 emissions are reduced with additional renewable power production in Norway, and it has been suggested to invest in wind power in order to completely offset the GWP of the STII energy system.

This paper provides investment analyses for the proposed energy system. A scenario approach was used, with six different scenarios covering two dimensions. The first dimension is the origin of the grid power, with three different interpretations of marginal power, i.e. hydro power, market mix and coal power, represented as Case A, B and C, respectively. The other dimension is the STII train size, with two different sizes being analyzed, namely 50 % and 70 % of the Snøhvit Train I design capacity.

The power demand of the two train sizes was estimated to 101 MW and 141 MW, with corresponding heat demand of 94 MW and 131 MW. These estimates were based on a combination of HYSYS simulations and data provided by StatoilHydro (SH), and provided input for both the GWP analysis and the investment analysis.

The GWP impact of each scenario without wind power determined the share of power import from the grid that would have to be replaced by energy harnessed from wind. The rated wind power to produce the needed amount of energy was thereafter determined by use of wind production estimates for Northern Norway. The applied capacity factor was 39.6 %, based on wind data from the Norwegian Institute of Meteorology. The share of wind power in the six scenarios ranged from 44 % to 80 %, corresponding to rated wind power requirements ranging from 101 MW in the A.50 scenario to 257 MW in the C.70 scenario. The former is the 50 % STII with power from the grid interpreted as being hydro power, the latter is the 70 % STII with power from the grid interpreted as produced in otherwise idle coal power plants. The annual wind power production in scenario C.70 is 893 GWh in comparison to a total power requirement of 1,120 GWh

The proposed energy system was also analyzed with respect to security of supply. Improved reliability and transmission capacity, together with a stable, positive power balance, make a good foundation for security of power supply. First, expected transmission capacity is in the order of 600 MW, and is expected to grow with new power consumers such as STII. This capacity will come in place with the new 420 kV Balsfjord-Hammerfest line, which is scheduled for commissioning in 2016. Second, the power balance in the three northernmost counties is about 2 TWh, and is expected to increase slightly until 2025. Third, the proposed energy system is expected to improve power supply reliability relative to Snøhvit Train I, which is supplied from LM 6000 gas turbines. The reliability of power import of 99.95 % is superior to the reliability of LM 6000 gas turbines, which have been reported in the range from 99.14-

99.70 %. Moreover, a solution based on gas turbines would require standby capacity to allow for regular maintenance without reducing the availability. Both capital and operational expenses related to this standby capacity are avoided with the proposed energy system.

The break even (BE) energy prices were calculated for each of the six scenarios analyzed, with the baseline that SH must pay a share of the Balsfjord-Hammerfest grid reinforcement, and that wind power will be developed in order to offset GWP. Contrarily, if the power consumption is based solely on power import with zero SH share of grid reinforcements and no SH development of wind power, the BE power price would be 466 NOK/MWh. In short, the inclusion of wind power development as part of the investment will increase the BE power price by up to 33 NOK/MWh. The additional SH share of grid reinforcement will add 86 NOK/MWh for the 50 % STII or 62 NOK/MWh for the 70 % STII. The BE heat price for all scenarios was found to be 283 NOK/MWh (2009 NOK).

It was shown that the investment in wind power to offset the GWP of the energy system might also be a reasonable way of hedging against increase in the market price of electricity. Moreover, the share of STII power demand that is covered by wind power was studied in a sensitivity analysis, and was shown to be one of the parameters that have the least influence on the project's net present value (NPV). The proposed energy system thus has the potential to boost the company's reputation as developer of sustainable solutions and to open new business opportunities without negatively impacting the project economy. Assuming that the capital expenditures of wind power do not change drastically, a high share of wind power is an inexpensive investment in reputation and predictability of energy price.

Through a screening of possible investment objects, suitable wind power projects were found with a total production estimate of about 4,300 GWh. The scenario requiring the most wind power in order to become GWP neutral would, in comparison, only require 893 GWh.

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APPENDICES

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Appendix A: Simulations

A.1 Energy rate balance

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_{inlet} \dot{m}_i \cdot \left(h_i + \frac{V_i^2}{2} + g \cdot z_i \right) + \sum_{exit} \dot{m}_e \cdot \left(h_e + \frac{V_e^2}{2} + g \cdot z_e \right) \quad \text{(A.1)}$$

where

$\left[\frac{dE_{CV}}{dt}\right]$ = *system total energy change per time*

$\left[\dot{Q}_{CV}\right]$ = *heat energy transferred over the system boundaries per time*

$\left[\dot{W}_{CV}\right]$ = *work energy transferred over the system boundaries per time*

$\left[\dot{m}_i h_i\right]$ = *thermal energy of mass that crosses the system boundaries per time*

$\left[\dot{m}_i \frac{V_i^2}{2}\right]$ = *kinetic energy of mass that crosses the system boundaries per time*

$\left[\dot{m}_i g z_i\right]$ = *potential energy of mass that crosses the system boundaries per time*

The liquefaction plant can be described by one hot and one cold stream, the latter one taking up heat from the former as illustrated in figure A.1.1. One can assume steady conditions, adiabatic heat exchange, no work exchange with the surroundings, and no change in the system's potential or kinetic energy.

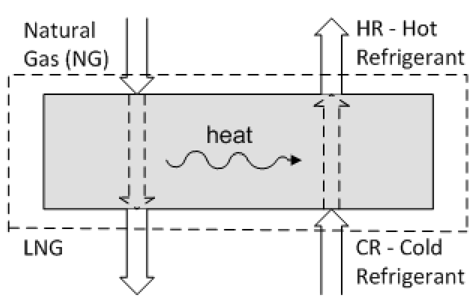

Figure A.1: Principal diagram of heat transfer for liquefaction of natural gas

The mass flow of the hot stream is connected to the mass flow of the cold stream by the stream enthalpies. The natural gas stream shall be cooled to the same temperature, at the same pressure, independently of its mass flow rate. The heat is transferred to the refrigerant, and the ratio of refrigerant stream enthalpy change over natural gas stream enthalpy change can therefore be regarded constant.

$$\dot{m}_{NG} = \dot{m}_R \cdot \frac{(h_{HR} - h_{CR})}{(h_{NG} - h_{LNG})} \quad \Rightarrow \quad \dot{m}_{NG} = \dot{m}_R \cdot CONSTANT \tag{A.2}$$

A.2 HYSYS Assumptions

HYSYS input, full capacity train

HHC Removal	Condenser temperature	-52,8	C
	Condenser pressure	59	bar
	Reboiler temperature	85	C
	Reboiler pressure	59	bar
	Number of stages	5	
	Feed enter at stage (bottom=1)	5	
Precooling refrigerant	Mass flow total	1480000	kg/h
	Mass flow Middle pressure	940000	kg/h
	Mass flow Low pressure	540000	kg/h
	Pmax cycle	14,8	bar
Liquefaction refrigerant	Mass flow	490000	kg/h
	Pmax cycle	24,5	bar
Subcooling refrigerant	Mass Flow	610000	kg/h
	Pmax cycle	52	bar
	Expander outlet pressure	8	bar
Natural gas stream	Feed pressure	62	bar
	Feed temperature	13	C
	Feed mass flow (4.3 Mtons p.a.)	627000	kg/h
	Temp at HHC Column inlet	-23,8	C
	Temp at SWHE 1 inlet	-52,8	C
	Temp at SWHE 2 inlet	-75	C
	Temp at LNG Expander inlet	-155,4	C
	LNG Expander outlet pressure	3	bar
	LNG throttle outlet pressure	1,2	bar
Sea Water	Sea Water temperature	6	C
	Sea Water Pump delta P	5	bar
	deltaT SeaWater/gas	10	C
	deltaT SeaWater/liquid	5	C
	max deltaT SeaWater in SW coolers	8	C

Table A.1: Input to HYSYS

A.3 Intermediate compressor pressure

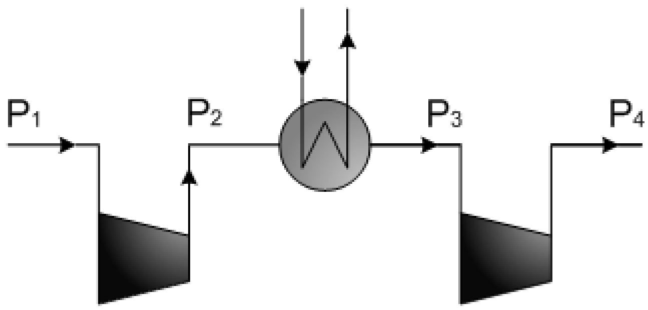

Figure A.2: Compression with inter-cooling

$$\frac{P_2}{P_1} = \frac{P_4}{P_3} \quad where \quad P_3 = P_2 - \Delta P \quad with \quad \Delta P > 0$$

gives

$$P_2\left(P_2 - \Delta P\right) = P_4 P_1 \quad \Rightarrow \quad P_2^2 - \Delta P P_2 - P_4 P = 0 \tag{A.3}$$

which can be solved for P_2 :

$$P_2 = \frac{\Delta P + \sqrt{\Delta P^2 + 4 P_4 P_1}}{2}$$

A.4 HYSYS flow rates and compositions

	Mw	LHV at 25'C	feed	HHCcolumn btm	HHCcolumn OVHD	flashgas	lng
Nitrogen	28,013	0,000	0,027	0,000	0,044	0,289	0,013
Methane	16,043	50,009	0,864	0,132	0,817	0,711	0,910
Ethane	30,069	47,794	0,065	0,236	0,097	0,000	0,060
Propane	44,096	46,357	0,027	0,295	0,034	0,000	0,015
Nbutane	58,123	45,752	0,012	0,227	0,006	0,000	0,002
i-butane	58,123	45,613	0,000	0,000	0,000	0,000	0,000
n-pentane	72,149	45,357	0,004	0,073	0,000	0,000	0,000
i-pentane	72,149	45,241	0,000	0,000	0,000	0,000	0,000
n-hexane	86,176	44,752	0,002	0,036	0,000	0,000	0,000
H_2O	18,015	0,000	0,000	0,000	0,000	0,000	0,000
CO_2	44,010	0,000	0,000	0,000	0,000	0,000	0,000
LHV at 25'C [MJ/kg]			48,35	46,90	47,41	35,57	49,17
Mw [kg/kmol]			18,87	43,86	19,19	19,50	17,54
Molar flow rate [kmol/h]							
100 %			33233	1541	31692	1735	29957
70 %			23263	1079	22184	1215	20970
50 %			16617	771	15846	868	14978
Thermal content [MW]							
100 %			8421	881	8010	334	7178
70 %			5895	616	5607	**234**	5024
50 %			4210	440	4005	**167**	3589
Furnace efficiency	0,90						
Furnace heat [MW]							
100 %			7579	793	7209	301	6460
70 %			5305	555	5046	211	4522
50 %			3789	396	3605	150	3230

Table A.2: flow rates, compositions and thermal content

A.5 Composite cooling curve

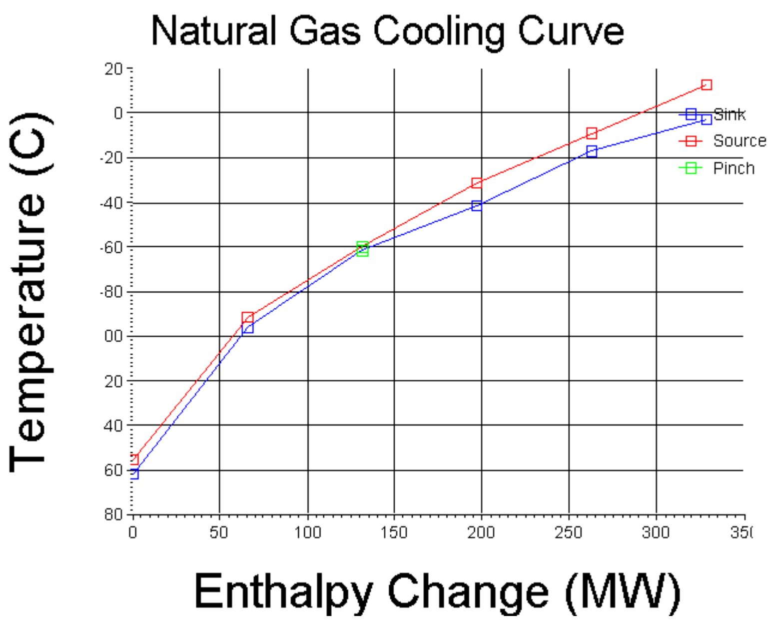

Figure A.3: Composite cooling curve for NG from HYSYS

Appendix B: RIVA

The reliability of power import can be investigated by performing a risk and vulnerability analysis (RIVA). The purpose of performing a RIVA is to identify potential risk factors and threats along the way, and to make clear which preventive action that may be taken to avoid disturbances to the power supply.

Risk can be understood to be an expression for the danger that unwanted incidents represent to humans, the environment or property, and can be described by the probability and consequences of these unwanted incidents (Standard Norge 2008). The analysis was also anticipated to yield a basis for later, more thorough analyses.

The approach for doing the RIVA can be split in 5 different phases as depicted in figure B.1:

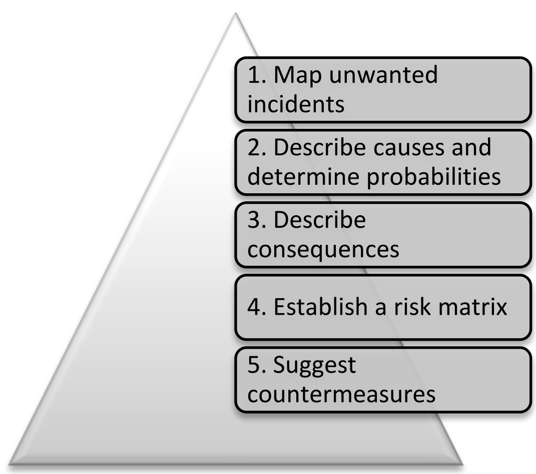

Figure B.1: Five different phases of the RIVA

Map unwanted incidents

In the case of power supply to STII, the essential goal is to be able to take off the desired amount of power from the grid, at any time. Every incident that can influence on this would therefore be of interest. A natural approach to identifying possible incidents was to look for relevant experience and research literature on the matter.

Describe causes and determine probabilities

Possible causes to the incidents listed earlier must also be identified, in order to determine the possibility for the incidents to occur. The causes can be of different character, e.g. technical faults or human or organizational errors. After having listed possible causes to each incident, preventive actions to each cause should be put down as well.

The probability of each incident had to be assigned a probability. The probabilities were classified in four categories ranging from very unlikely to very likely, as depicted in figure B.2.

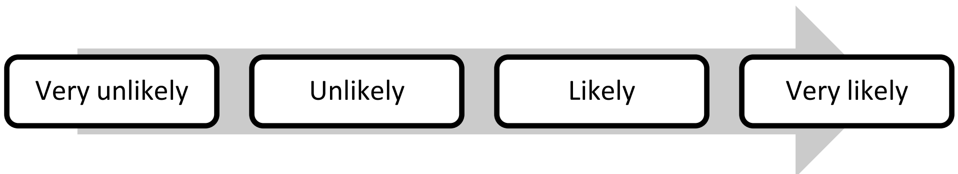

Figure B.2: Classification of probability from very unlikely to very likely

It is given an integer value ranging from 1 to 4 for each of the probabilities, where incidents being assigned the highest value are the most probable. NVE (2005 #2) suggests a framework for assigning probabilities based on how often the incidents occur. This framework is reproduced in table B.1.

Grading of probability

Term	***Level***	***Description of probability***
Very likely	**4**	>1 per year
Likely	**3**	>1 per 10 years
Unlikely	**2**	>1 per 50 years
Very unlikely	**1**	<1 per 50 years

Table B.1: Framework for grading probabilities (NVE 2005 #2)

Statistical data was looked for in order to determine the probability for causes to occur. The available data were not sufficiently specific; fault and power cut statistics are not split geographically and with respect to different line voltages.

Describe consequences

Incidents can be arranged in a systematic manner by ranging them with respect to the extent of damage they entail. It is suggested to arrange the consequences in one of the five categories ranging from safe to catastrophic as depicted in figure B.3.

Figure B.3: Classification of consequences from safe to catastrophic

Each of these labels defines a level of consequence with respect to different perspectives; humans, the environment, economic value and so forth. The evaluation of consequences is best given account for by tabulating consequence criticality labels together with a description from each relevant perspective. The most critical incidents are given the highest integer value. An example of consequences grading is given in table B.2.

Grading of consequences

		Description of consequence		
Term	Level	HUMANS	ENVIRONMENT	ECONOMIC LOSS
Safe	**1**	No personal injuries	No environmental damage	< 10 000 NOK
A little hazardous	**2**	Few and minor personal injuries	Minor environmental damage	< 100 000 NOK
Hazardous	**3**	Few but serious personal injuries	Extensive environmental damage	< 1 MNOK
Critical	**4**	1 death, <5 serious injuries, <100 evacuated	Serious, hazardous environmental damage	< 10 MNOK
Catastrophic	**5**	>1 death, >5 serious injuries, >100 evacuated	Very serious and long-lasting environmental damage	> 10 MNOK

Table B.2: Framework for grading of consequences (NVE 2005 #2)

Establish a risk matrix

A risk matrix can be formed by realizing that risk is the product of probability and consequence. Incidents can be plotted in the risk matrix, and further action can then be based on a set of accept criteria.

Suggest countermeasures

Accept criteria help decide whether countermeasures are needed to reduce risk. The risk matrix can lead to preventive action that lowers the probability for incidents to occur or minimizes the extent of damage of incidents. The risk analysis can then be repeated to see if residual risk is acceptable, and to establish emergency response plans to handle this risk.

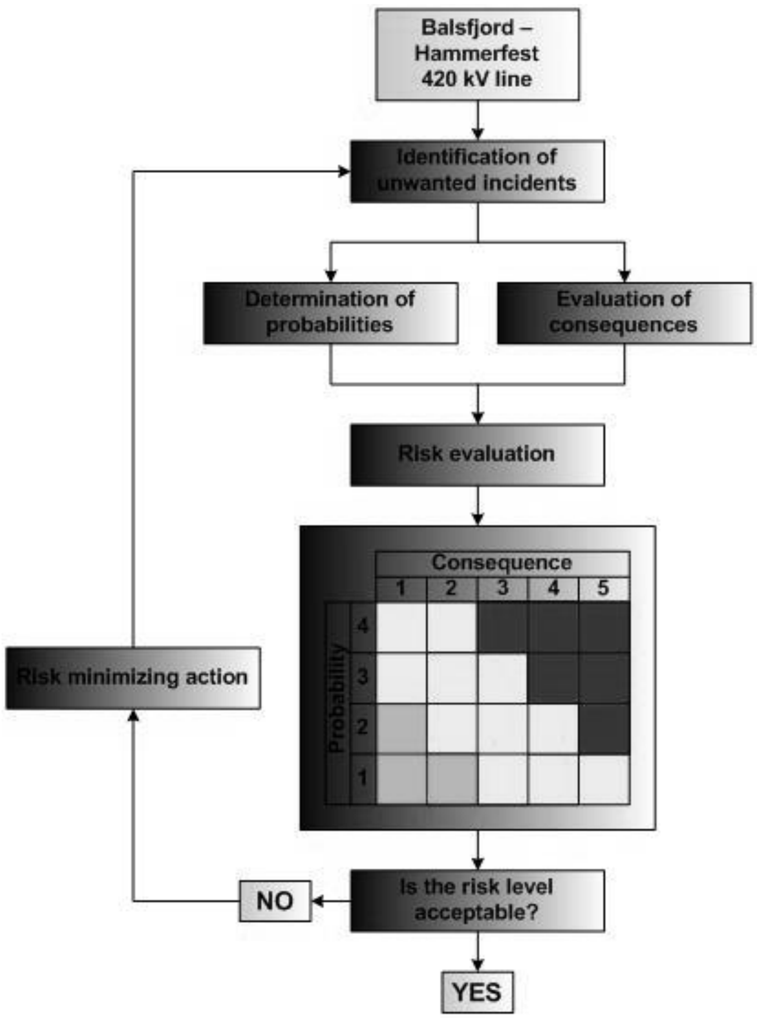

Figure B.4: RIVA flow diagram

Appendix C: SimaPro and Ecoinvent system processes

CASE A: Electricity, hydropower, at power plant/NO S

Included processes: Includes shares of electricity produced by of run-of-river and reservoir hydropower plants.

Remark: Electricity production shares are determined on annual average and on the level of net production; Geography: Valid for this single country.

Technology: Not applicable because the dataset just describes shares.

Version: 2.0

CASE B: Electricity mix/NO S

Included processes: It includes the shares of domestic electricity production by technology and imports from neighboring countries (production mixes) at the busbar. It does not include transformation, transport nor distribution losses.

Remark: Electricity domestic net production and import shares are based on annual averages; Geography: Data apply to public and self producers in Norway. It includes imports from Denmark, Finland, Sweden and Russia.

Hard coal, natural and industrial gas power plants are modeled using NORDEL averages. Oil power plant is modeled using Finnish average oil power plant.

Technology: No technology description is provided because the dataset just describes the power plant portfolio (including imports) of the respective country using current (2000) average technology per energy carrier.

Time period: Time period of statistics used.

Version: 2.0

CASE C: Electricity, hard coal, at power plant/NORDEL S

Included processes: Electricity output at busbar. The module uses the average net efficiency of hard coal power plants in NORDEL countries.

Remark: The module describes the electricity production of an average plant for the country. The plant is used for middle load with 4000 hours of operation at full capacity per year. The plant is assumed to operate 150000 hours during its lifetime. For the assessment of main characteristics (LHV, sulphur and ash content of coal, efficiency of the plant) and criteria emissions (SOx, NOx, particles, and CO2) a bottom-up approach has been used. It consists on the collection of information about single plants. Base data on all major UCTE power plants in 1993 have been integrated, to the extent possible, with updated information for year 2000. The size distribution of particles has been derived from German data. Halogene emissions have been estimated on the basis of the content of the species in the country-specific coal input mix, assuming average retention rates. For CO and VOC-emissions average values for UCTE are included. Two average values for N2O emissions from UCTE plants are considered for the two cases with or without DeNOx; the country specific emission depend therefore on the share of DeNOx. Emissions of trace elements were calculated by means of a formula (CORINAIR) using the ash content in the country-specific coal input mix and average transfer coefficients for coal power plants, taking into account the share of DeSOx installed. Emissions of uranium and thorium radioactive isotopes were assumed proportional to the corresponding element emitted with particles; the other non-gaseous radioactive isotopes of the uranium and thorium decay chain were assumed proportional to the emitted U-238 or Th-232. The emission of gaseous radon and K-40 are taken from the literature. The waste heat releases to air and water have been allocated on the basis of the assumed share of river cooled power plants and assumptions on the direct losses to air. The share of the recycled ash is country-specific. For the disposal of the remaining ash, typical country-specific compositions are taken into account in appropriate disposal modules; Geography: Country-specific data.

Technology: Average installed technology.

Version: 2.0

HEAT SUPPLY: Refinery gas, burned in furnace/MJ/RER S

Processes included: Consumption of refinery gas and emissions from combustion.

Remark: Description of the direct emissions due to the combustion of refinery gas in refinery furnaces and generators not including the infrastructure of the furnace. Geography: Data for single European plants.

Technology: Average technology in use. There might be large differences for single plants due to the technology used for the flue gas treatment.

Time period: New European data from single plants for regulated emissions like CO2, NOx, SOx etc. have been provided in the literature. They have been compared and discussed with older literature data.

Version: 2.0

Appendix D: Wind farming projects

Ref. on map	Project Name	Project Owner	Location	Municipality	Rated power [MW]	Status	Criterion 1	Criterion 2	Criterion 3	Weighted score	Suitable for STII	Production estimate [GWh]
18	Snefjord Vidpark	StatoilHydro	Finnmark	Måsøy	160	Applied for license	3	2	3	2,7	✓	555,0
19	Hammerfest Vindpark	Statkraft Energi AS	Finnmark	Hammerfest	110	Applied for license	3	2	3	2,7	✓	381,6
30	Nygårdsfjellet trinn 2	Nordkraft Vind AS	Nordland	Narvik	40	License granted, not operating	2	3	3	2,7	✓	138,8
22	Fakken Vindpark	Troms Kraft Produksjon AS	Troms	Karlsøy	60	License granted, not operating	2	3	3	2,7	✓	208,1
27	Kvitfjell Vindpark	Norsk Miljøkraft Tromsø AS	Troms	Tromsø	200	License granted, not operating	2	3	3	2,7	✓	693,8
20	Dønnesfjord Vindpark	Vindkraft Nord AS	Finnmark	Hasvik	100	Notified	3	1	3	2,3	✓	346,9
25	Raudfjell	Norsk Miljøkraft	Troms	Tromsø	180	Applied for license	2	2	3	2,3	✓	624,4
31	Andmyran	Andmyran Vindpark AS	Nordland	Andøy	160	License granted, not operating	2	3	1	2,0	✓	555,0
38	Sørfjord	Nordkraft Vind AS	Nordland	Tysfjord	160	Notified	2	1	3	2,0	✓	555,0
24	Rieppi Vindpark	Troms Kraft Produksjon AS	Troms	Nordreisa	63	Notified	2	1	3	2,0	✓	218,5
5	Båtsfjordfjellet	StatoilHydro	Finnmark	Båtsfjord	120	Applied for license	2	2	1	1,7	✗	-
7	Hamnefjell	StatoilHydro	Finnmark	Båtsfjord	160	Applied for license	2	2	1	1,7	✗	-
9	Ràkkocearro	Varanger Kraft-produksjon AS	Finnmark	Berlevåg	350	Applied for license	2	2	1	1,7	✗	-
14	Laksefjorden	Fred. Olsen Renewables AS	Finnmark	Lebesby	100	Applied for license	2	2	1	1,7	✗	-

15	Digermulen	Fred. Olsen Renewables AS	Finnmark	Gamvik	100	Applied for license	2	2	1	1,7	✗	-
10	Eliastoppen	Norsk Miljøkraft FOU AS	Finnmark	Berlevåg	40	Notified	2	1	1	1,3	✗	-
11	Nordkyn Vindpark	Statkraft Develop-ment AS	Finnmark	Lebesby, Gamvik	750	Notified	2	1	1	1,3	✗	-
12	Skjøtningsberg	Norsk Miljøkraft FOU AS	Finnmark	Lebesby	400	Notified	2	1	1	1,3	✗	-
0	Bjørnevatn	Troms Kraft Produksjon AS	Finnmark	Sør-Varanger	60	Notified	2	1	1	1,3	✗	-
32	Skavdalsheia	Fred. Olsen Renewables AS	Nordland	Andøy	40	Notified	2	1	1	1,3	✗	-
37	Gimsøy	Lofotkraft Vind AS	Nordland	Vågan	50	Notified	2	1	1	1,3	✗	-
46	Sjonfjellet	Nord-Norsk Vindkraft AS	Nordland	Rana	360	Notified	1	2	1	1,3	✗	-
47	Sleneset	Nord-Norsk Vindkraft AS	Nordland	Lurøy	225	Applied for license	1	2	1	1,3	✗	-
41	Seiskallåfjellet	Nord-Norsk Vindkraft AS	Nordland	Rødøy	147	Notified	1	1	1	1,0	✗	-
48	Kovfjellet	Nord-Norsk Vindkraft AS	Nordland	Vefsn	57	Notified	1	1	1	1,0	✗	-
49	Stortuva	Nord-Norsk Vindkraft AS	Nordland	Vefsn	69	Notified	1	1	1	1,0	✗	-
50	Mosjøen	Fred. Olsen Renewables AS	Nordland	Vefsn	300	Notified	1	1	1	1,0	✗	-
51	Kalvvatnan	Fred. Olsen Renewables AS	Nordland	Bindal	225	Notified	1	1	1	1,0	✗	-
	Total										□	**4 277,2**

Figure D.1: Wind farming projects in the vicinity of STII