NTNU – Trondheim
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Exergy analysis of conventional and electrified oil and gas platforms

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Submission date: June 2014
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NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2014-86

MASTER THESIS

for

Student Luke Kollerøs Panton

Spring 2014

Exergy analysis of conventional and electrified oil and gas platforms

Eksergianalyse av konvensjonelle og elektrifiserte olje og gass plattformer

Background and objective

It is currently a requirement by the Norwegian Authorities to evaluate the supply of electric power from shore (electrification) for all new oil and gas offshore installations. This evaluation will be case specific due to different power and heat requirements, but also because of different installation types, locations and available connection points to the onshore grid. In this thesis, the different levels of electrification of generic oil and gas producing platforms will be evaluated from an energy efficiency point of view. The different forms of energy shall be taken into account by means of exergy analyses. The results shall be discussed with regard to the suitability for electrification of an oil platform and a gas platform with focus on overall energy and exergy efficiencies as well as CO2 emissions.

The main objective of this master thesis project is thus to come up with recommendations whether electrification of generic oil and gas platforms makes sense from an energy and environmental point of view. Different scenarios for partial or full electrification (see the detailed tasks below) will be evaluated. Since different energy forms are handled, exergy analysis will be used to substantiate these recommendations. In addition to exergy efficiency, energy efficiency figures will also be obtained while keeping a focus on CO_2 emissions.

The following tasks are to be considered:

1. Study relevant literature dealing with exergy analyses of production processes, especially oil and gas platforms.
2. Define the system boundaries/control volumes to be used for the exergy analyses by considering all relevant material and energy streams for the following cases:
   a. Conventional heat and power supplied by gas turbines and waste recovery units on the platform
   b. Power from shore and heat supplied by gas fired heaters on the platform

   c. Power from shore supplying both heat and power to the platform
   d. Alternative sources of power supplied from shore shall be considered:
      i. Emission free hydro power plant located in Norway
      ii. Combined cycle gas power plant located in Norway
      iii. Combined cycle gas power plant located in Germany

3. Set up exergy balance equations considering all relevant exergy losses.
4. Carry out external exergy analyses for both an oil platform and a gas platform (plateau and late life) for the cases above on the basis of the HYSYS models developed during the project work during the fall 2013.
5. Discuss the results by comparing the energetic and exergetic efficiencies for an oil platform and a gas platform for the different cases with regard to suitability for electrification. Further, the results should also be discussed with regard to CO_2 emissions on a qualitative basis.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14 January 2014

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Preface

This thesis constitutes the final assignment of my master's program at the Institute for Heat and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. It has been written in collaboration with Aker Solutions' Front End Spectrum department in Oslo.

My supervisors from Aker Solutions, Björn Eide and Thomas Førde, have never hesitated to answer questions, discuss problems and give me a push when I have needed it. Thank you, I appreciate it. You will both be missed.

My NTNU supervisor Truls Gundersen has been a faithful Skype buddy for the past semester, where we have discussed thermodynamics, efficiencies, energy, exergy, Truls' cabin and much more. Thank you for all of your input.

Aker Solutions has provided me with all of the hardware I have required, the necessary simulation software and a vibrant workplace full of talented individuals, from which I have benefitted greatly. Writing this thesis with Aker Solutions is an opportunity which I have been lucky to have. Thank you.

Finally, I would like to thank my wife Kristine and my boys Harald and Alfred, for putting up with my absence on many an evening this spring. I'm back.

Abstract

This paper compares the efficiencies of oil and gas producing offshore platforms, at different points in the production lifetime and for different heat and power supply options by means of energy and exergy analysis. Offshore platform electrification is a tool being employed by the Norwegian government in order to meet its emission reduction promises. The electrification of offshore platforms however, may not always lead to a higher overall system efficiency or the reduction of CO_2 emissions when onshore power production and transmission are taken into account.

Aspen HYSYS platform simulations have been made, where heat and power duties are supplied by either gas turbines, partial electrification or full electrification. Stream property data has then been exported to spreadsheets where data for the electrification option power sources (Norwegian hydro power and German combine cycle gas power) have been calculated. Finally, energy and exergy efficiencies, as well as CO_2 emissions, were calculated for each case.

For the gas platform, electrification reduced CO_2 emissions and increased the lifetime energy and exergy efficiencies when compared to the gas turbine case. This result was independent of where the power originated. For the oil platform, all of the electrification options except for one, gave emission decreases and efficiency increases. The oil platform with full electrification from a German CCGT plant led to an overall system efficiency decrease and increased CO_2 emissions. In general, electrification of the gas platform led to greater efficiency gains and emission reduction than electrification of the oil platform.

This paper provides a slightly different perspective on the issue of offshore platform electrification. It illustrates how exergy analysis can be used to compare whole systems, and highlights some of the issues associated with the methods used. This type of analysis could be employed by governments and oil companies as part of an electrification evaluation process.

Sammendrag

Målet med denne masteroppgaven var å sammenligne olje- og gassproduserende offshore-plattformer. Energi- og eksergianalyseranalyser ble utført på forskjellige stadier i livsløpet til plattformene, og med ulike løsninger på kraft- og varmeforsyning. Sokkelelekrifisering er et av tiltakene som den norske staten har bestemt seg for å ta i bruk for å nå klimamålene. Men det er ikke sikkert at elektrifisering av sokkelen vil føre til effektivisering av produksjonen og utslippskutt, om landbasert kraftgenerering og overføring taes med i beregningen.

Aspen HYSYS-simuleringer ble konstruert, der kraft- og varmebehovene til plattformene enten ble dekket av gassturbiner, delelektrifisering eller helelektrifisering. Informasjon om HYSYS-strømmene ble eksportert til regneark hvor data for elektrifiseringskildene (Norsk vannkraft og Tysk combined cycle gasskraftverk) også ble beregnet. Til slutt ble energi- og eksergivirkningsgrader, samt CO_2-utslipp, beregnet for hver case.

På gassplattformen reduserte elektrifisering CO_2-utslippene og økte energi- og eksergivirkningsgradene, uavhenging av kraftens kilde. På oljeplattformen førte alle elektrifiserings løsningene bortsett fra en, til økte virkningsgrader og utslippsreduksjon, i forhold til gassturbinløsningen. På den helelektrifiserte oljeplattformen, hvor kraften kom fra et tysk gasskraftverk, var energi- og eksergivirkningsgradene lavere og CO_2-utslippene høyere enn det tilsvarende tilfellet på gassplattformen. Generelt sett, førte elektrifisering av gassplatformen til en større økning i virkningsgradene enn elektrifisering av oljeplattformen.

Denne masteroppgaven bidrar med et litt annet perspektiv til debatten om elektrifisering av sokkelen. Den viser hvordan en eksergianalyse kan bli brukt til å sammenligne hele systemer, samtidig som noen av utfordringene med metoden er diskutert. Denne typen analyse kunne blitt brukt av staten og oljeselskaper som en del av prosessen hvor elektrifisering blir vurdert.

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Nomenclature

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Symbol	Units	Description
$\mathbf{E}$	[kJ]	Exergy
E	[kJ]	Energy
t	[s]	Time
T_0	[°K]	Environmental reference temperature
T_j	[°K]	Temperature of heat transfer *j*
$\dot{Q}_j$	[kW]	Rate of heat transfer *j*
$\dot{W}_{cv}$	[kW]	Rate of work done by the control volume
p_0	[bar]	Environmental reference pressure
V_{cv}	[m³]	Volume of the control volume
$\dot{n}_i n$	[kmol/s]	Inlet stream molar flow rate
$\dot{n}_{out}$	[kmol/s]	Outlet stream molar flow rate
$\bar{\boldsymbol{e}}_{fin}$	[kJ/kmol]	Molar flow exergy (inlet)
$\bar{\boldsymbol{e}}_{fout}$	[kJ/kmol]	Molar flow exergy (outlet)
$\dot{\mathrm{E}}_d$	[kW]	Rate of exergy destruction
$\bar{\boldsymbol{e}}^{tm}$	[kJ/kmol]	Molar thermomechanical flow exergy
$\bar{\boldsymbol{e}}^{ch}$	[kJ/kmol]	Molar chemical flow exergy
$\bar{\boldsymbol{e}}^{pot}$	[kJ/kmol]	Molar potential flow exergy
$\bar{\boldsymbol{e}}^{kin}$	[kJ/kmol]	Molar kinetic flow exergy
$\bar{h}$	[kJ/kmol]	Molar enthalpy
$\bar{h}_0$	[kJ/kmol]	Environmental reference molar enthalpy
$\bar{s}$	[kJ/kmol · K]	Molar entropy
$\bar{s}_0$	[kJ/kmol · K]	Environmental reference molar enthalpy
x_i	-	Mole fraction of the i'th comp. of a gas mixture
y_i	-	Mole fraction of the i'th comp. of a liquid mixture
x	-	Gas fraction of a two-phase flow
y	-	Liquid fraction of a two-phase flow
z_i	-	Overall molar fraction of the i'th comp. in a two-phase mixture
C1, C2, C3, etc.	-	Hydrocarbons – methane, ethane, propane, etc.
$\overline{\mathrm{HHV}}$	[kJ/kmol]	Molar higher heating value
$\overline{\mathrm{LHV}}$	[kJ/kmol]	Molar lower heating value
η_{ex}	-	Exergy efficiency
$\dot{n}_{prod}$	[kmol/s]	Molar flow rate of the system products
$\bar{\boldsymbol{e}}_{f,prod}$	[kJ/kmol]	Molar flow exergy of the system products
$\bar{h}_{prod}$	[kJ/kmol]	Molar flow enthalpy of the system products
$\bar{h}_{th}$	[kJ/kmol]	Thermal enthalpy
$\dot{\boldsymbol{E}}_{prod}$	W	Exergy flow of the system products
$\dot{\boldsymbol{E}}_{fuel}$	W	Exergy flow of the fuel
PW		Produced water
SW		Seawater

1 Introduction

The extent to which climate change is occurring and its effects are becoming ever clearer [1]. While there is a general consensus for this, there is less agreement on which strategies should be employed to combat climate change and fulfil national emission reduction commitments. The Norwegian government has decided that the electrification of offshore platforms is one of the measures that must be considered. This proposal has led to heated dispute, played out both in the media and political arena with the merits and faults of the plan being debated heatedly. Some of the apparent advantages of electrification are a reduction in CO_2 emissions and higher efficiencies due to the replacement of offshore gas turbines with relatively high efficiency land based power generation [2].

The aim of this thesis is to test whether the electrification of offshore platform is beneficial, from the perspective of efficiency and CO_2 emissions. This will be tested by first establishing an energy and exergy analysis calculation program in Excel, after a review of the literature. Control volumes will then be constructed for a range of different scenarios where the platform as well as its land-based (or offshore) heat and power generation and transmission are included. The different cases will then be compared using the efficiencies and CO_2 emissions calculated after feeding simulation data into the Excel program.

This master thesis follows a previous project thesis completed in the autumn of 2013 entitled – “Energy requirements of an oil and gas producing platform in the North Sea” [3]. This project thesis deals heavily with the development of the HYSYS simulations which have been used in this master’s thesis. It is recommended that the reader be familiar with the project thesis in order to better understand the master thesis’ foundation, especially if the simulations are of interest.

2 Literature review

The use of exergy analyses to determine the efficiencies of different process plants and sub-systems of these plants is relatively new. A unifying aspect of the offshore platform exergy analysis paper's looked at in connection with this literature review, is their treatment of each of the sub-systems of the platform separately, and an aim to find where efficiencies can be improved on the platform.

The first platform exergy analysis paper found was published in 1997 and written by Oliveira and Hombeeck [4]. Although relatively simplistic in comparison to the many of the papers published since, this paper established a standard. Many of the following papers, by other authors, compare their results with this analysis as well as using some of the methods established here, such as the *f* factor, which grades the amount of exergy destroyed in each sub-system. Oliveira analyses the separation, compression and pumping modules on a typical Brazilian offshore platform and finds that it is in the separation process that the greatest portion of the exergy is destroyed.

In recent years, Tuong-Van and Voldsund have published multiple papers on the topic. They have written a number independently of each other, while also collaborating on a number of papers more recently. In a number of these papers, an exergy analysis has been conducted on platforms in the same fashion as that done by Oliveira. Voldsund. Et. al [5], in one of her first papers on the topic, conducts an exergy analysis on a typical North Sea oil and gas producing platform. The paper is a more rigorous example of an exergy analysis where separation, recompression, injection and oil export are analysed separately. Voldsund found that the majority of the exergy destruction occurred in the gas injection compression trains. Voldsund has also written a similar paper where an exergy analysis has been carried out using different platform data from a real production day [6].

Tuong-Van, in his paper from 2010 [7], uses a similar methodology to Voldsund. In addition to conducting exergy analyses on the platform sub-systems, the gas turbine power generation system was also analysed and found to account for about twice the exergy destruction as in the oil and gas processing system.

Voldsund and Tuong-Van have written two paper in collaboration. The first of these papers attempts to establish a system for comparing different platform operating under different conditions [8]. The other paper is a comparison of four North Sea platforms where it was found, once again, that the greatest losses were in the gas compression sub-systems[9].

One of the exergy analysis papers reviewed had a land based process plant as its subject. Rian Et al. [5] conducts an energy and exergy analysis on the gas liquefaction plant – Snøhvit – in northern Norway. The liquefaction process is very different to that which occurs on an oil and gas processing platform, but there are a number of similarities otherwise. Rian calculated an overall plant energy efficiency to be 93.3 % and the exergy efficiency to be 95 %. The energy efficiency being higher than the exergy efficiency is due to the fact that the cold LNG product has a high exergy flow rate (large temperature differential between stream and environmental conditions) but a relatively low energy flow rate (the colder the product the less energy contained in it). Rian's exergy efficiency is much higher than the previous platform analyses as the efficiency was calculated for the whole plant.

The exergy analysis methodology used in Tuong-Van and Voldsund's papers is very relevant for this paper and a great deal has been learned from them. However, due to the nature of the control volume in this thesis, the exergy efficiency calculation method used follows that of Rian Et al. (See Section 2.1 for more on this decision).

Late in the process of writing this thesis, another published version of Rian's article was found [10]. This article omitted the energy analysis and focused only on the exergy analysis. An alternative method of calculating the exergy efficiency was suggested, making it possible to compare the efficiencies with those calculated in the same fashion as Oliveira, Voldsund and Tuong-Van. Due to time constraints, this method was not included in this thesis.

2.1 Efficiency definition challenges

Defining the exergy efficiency is not a straight-forward task, a sentiment that was also encountered in the literature studied. A number of different ways of defining this efficiency were thus found, each with their respective advantages and disadvantages. The methods used were very dependent on the type of exergy analysis being performed and how the control volume was defined. There are some fundamental differences between an exergy analysis of a single sub-system or component operating in a process plant as opposed to analysing the whole plant as one system.

The challenge when defining the exergy efficiency is the chemical exergy of the components in a flow. The component chemical exergy of a substance tends to make up a large proportion of a stream's flow exergy and thus dominate any efficiency calculation. As an example, the different flow exergy contributions in the gas export pipeline are shown in Table 2-1 below (taken from the oil plateau case with gas turbine power generation).

Table 2-1 Example of the portion of the total exergy contributed by the different types of exergy (in the gas export stream in case 2a_O_p)

Exergy type	kJ/kmol	% of total
Component chemical exergy	1221656	99.21
Exergy of mixing	-1249	-0.10
Thermomechanical exergy	11021	0.89
Total	1231428	100

The component chemical exergy stands for over 99 % of the flow exergy, even in this stream which has a relatively high thermomechanical exergy due to its pressure and temperature.

The bulk of the oil and gas entering the platform in the wellstream leaves the platform as an oil or a gas product. Only small portion of the chemical exergy is lost as fuel gas to the gas turbine. When this exergy form in addition dominates the exergy total, the platform's exergy efficiency ends up close to unity. Both Voldsund [18] and Rian [10] discuss the implications of this. The high efficiency gives a misleading impression of the efficiency of the plant. The impact on the efficiency of any improvements made to the plant will also be reduced. It is difficult to argue that adjustments should be made to an existing or planned plant when the efficiency appears high, and when adjustment appears to have such a small impact.

Oliveira, Voldsund and Tuong-Van, in their platform exergy analyses primarily attempt to find the sub-systems where exergy destruction is greatest. By analysing each of the process sub-systems separately, the chemical exergy of the components can be cancelled out as the component chemical exergy entering and exiting is unchanged. In the case of a separation sub-system, only the exergy of mixing is changed. The entire processing part of the platform is also given an exergy efficiency in some of the papers, but in these cases the power generation utility system is excluded. As such the above-mentioned authors are able to avoid the efficiency problems associated with the large component chemical exergy values.

While a number of platform comparison measures are discussed (particularly in [8]) the most popular of the exergy efficiency equations used by these authors is given in Equation (2-1). It is defined as the exergy change (increase) in the mass streams divided by the exergy inputs – work and heat.

$$\eta_{ex} = \frac{\sum_e \dot{\boldsymbol{E}}_{out} - \sum_e \dot{\boldsymbol{E}}_{in}}{\sum_e \dot{\boldsymbol{E}}_{fuel}} \qquad (\ 2\text{-}1\ )$$

Rian [5] on the other hand uses the 'inlet-outlet' exergy efficiency in which the exergy of the product is divided by the exergy of all of the exergy streams entering the control volume (as used in this thesis and given in Equation (3-13)). The component chemical exergy is included in this calculation leading to relatively high efficiencies.

As mentioned above, a later publication of Rian's Snøhvit exergy analysis [10] included an alternate exergy efficiency (given in Equation (2-2)) which avoids the overly high efficiencies associated with the 'inlet-outlet' exergy efficiency. It is defined as the thermomechanical exergy and exergy increase in the product mass flows divided by the thermomechanical exergy of the feed stream plus the chemical exergy of the fuel gas portion of this stream. Due to time constraints and the point at which this publication was discovered, this efficiency variant was not tested.

$$\eta_{ex} = \frac{\sum_p \boldsymbol{E}_p^{tm} + \sum_p \boldsymbol{E}_p^{ch}}{\boldsymbol{E}_{feed}^{tm} + \sum_i n_{i,fuel}(\bar{\boldsymbol{e}}_{0,i} + \bar{R}T_0 \ln x_{i,feed})} \qquad (\ 2\text{-}2\ )$$

The aim of this thesis is not to isolate ineffective processes on the platform, but rather to compare different platform with different power supplies. Accordingly, the control volumes include all of the platform sub-systems, as well as land based power generation. It is primarily the power generation which makes it necessary to include the chemical exergy in the efficiency. In the platform gas turbines, German combine-cycle gas power plant and gas-fired burners, chemical exergy in the fuel gas streams is converted into power, exhaust heat and a new chemical composition in the exhaust. The component chemical exergy can as such not be cancelled out of the exergy efficiency equations. The ‘inlet-outlet’ exergy efficiency has thus been used in this thesis. This method still gives a good basis for comparison of the different cases studied.

3 Theory

3.1 Exergy theory

‘Exergy’ is a term used to describe the theoretical amount of work which can be obtained from a system. Other names for exergy include potential work, or availability [11]. The term was first coined in 1956, but the concept of work availability was already being studied in the 1800’s [12]. The exergy of an object or flow is very closely associated with the difference between the objects conditions and those of the environment. The greater the difference, the greater the potential to do useful work.

By using exergy as a tool to analyse the efficiency of a process, rather than energy, it is the quality of the energy which contributes to the efficiency. An example of the advantages of an exergy analysis, contrary to an energy analysis, is the energy loss associated with a power plants cooling medium. Large amounts of energy may be ‘lost’ as low temperature cooling water/air/etc. due to the large mass flow. The energy associated with this low temperature flow is very difficult to exploit in reality, but an energy analysis will not reflect this and the overall efficiency will be lowered due to this loss. The exergy contained in the same stream is however much less than the energy due to the relatively small difference between the stream’s temperature and that of the environment. The exergy efficiency of the plant will thus not be lowered as much due to the loss.

3.1.1 Environment

Moran Et. al. [13] defines the environment as a system’s surroundings, distant enough that its intensive properties (properties which are independent of system size e.g. temperature) are not affected by any interaction between it and the system.

When calculating exergy, actual conditions must be compared with a reference condition at which the system is in equilibrium with the environment. There is a difference between the states of equilibrium reached, for the different types of exergy calculations. Kotas [14] refers to two equilibrium states labelled restricted and unrestricted equilibrium. Restricted equilibrium exists when a system is in mechanical and thermodynamic equilibrium with its environment i.e. its pressure and temperature are equal to that of the environment. This form of equilibrium is referred to as the environmental state. Unrestricted equilibrium is achieved when a system, in addition to thermodynamic and mechanical equilibrium, is also in chemical equilibrium with the environment. When a system is in unrestricted equilibrium with its environment, it is not possible for the system to react with the environment in any manner and it is referred to as being in the dead state.

It should be noted that in the simulations used in this thesis, the actual environmental conditions differ from the ‘environmental state’ used for exergy calculation. The exergy environmental state (and dead state for that matter) is at STP conditions of T_0 = 25 °C, P_0 = 1 atm. and 60 % humidity. The Seawater and air temperatures are however set at 15 °C in the simulations. Setting the exergy reference environment to be at STP conditions is a pragmatic decision, based on the availability of standard chemical exergy data, as discussed further in Section 3.1.4.

3.1.2 Exergy rate balance

The control volume exergy rate balance is given by Equation (3-1).

$$\frac{d\mathbf{E}}{dt} = \sum_j (1 - \frac{\mathrm{T}_0}{\mathrm{T}_j})\dot{Q}_j - \left(\dot{W} - p_0 \frac{dV_{cv}}{dt}\right) + \sum_i \dot{n}_{in}\bar{\boldsymbol{e}}_{fin} - \sum_e \dot{n}_{out}\bar{\boldsymbol{e}}_{fout} - \dot{\mathrm{E}}_d \qquad (3\text{-}1)$$

The exergy transfer rate $\frac{d\mathbf{E}}{dt}$ is dependent on a number of terms in Equation (3-1). The first is the exergy of heat transfers to and from the system. This is defined as the Carnot efficiency of a heat machine operating between the environmental temperature T_0, and the temperature at which the heat transfer occurs T_j, multiplied by the actual energy transfer in the heat flow $\dot{Q}_j$. The next term consists of the work done due to expansion of the control volume $p_0 \frac{dV_{cv}}{dt}$, and other completely utilisable work such as electricity or shaft work $\dot{W}$. Then follows the inlet and outlet flow exergy and exergy destruction terms, which are described further down in this section.

It is important to note here the sign convention used when dealing with work and energy transfer in this thesis. The work W is considered positive in the case when work is done by the system, while all work that is done on the system has a negative value. Heat transfer has the opposite signage – heat transfer to the system is positive and heat transfer from the system is negative. Figure 3-1 illustrates this convention.

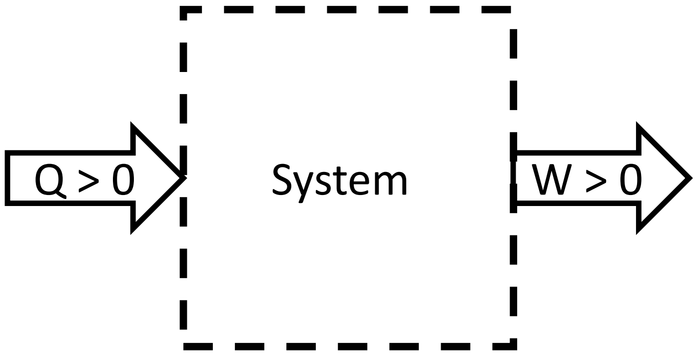

Figure 3-1 Example showing the direction of positive work (W) and positive heat (Q) transfer between a system and its surroundings.

For the cases studied in this thesis, the following assumptions are made:

- Assume 'stiff' control volume ($\frac{dV_{cv}}{dt} = 0$)
- Assume steady state operation ($\frac{d\mathbf{E}}{dt} = 0$)

The exergy rate balance is then given by Equation (3-2).

$$0 = \sum_j (1 - \frac{\mathrm{T}_0}{\mathrm{T}_j})\dot{Q}_j - \dot{W} + \sum_i \dot{n}_{in}\bar{\boldsymbol{e}}_{fin} - \sum_e \dot{n}_{out}\bar{\boldsymbol{e}}_{fout} - \dot{\mathrm{E}}_d \tag{3-2}$$

Sub-reference temperature heat transfer exergy

When a heat transfer occurs below the reference temperature, the heat transfer term in Equation (3-2) is given by Equation (3-3).

$$\sum_j (\frac{\mathrm{T}_0}{\mathrm{T}_j} - 1)\dot{Q}_j \tag{3-3}$$

Flow exergy

The molar flow exergy term $\bar{\boldsymbol{e}}_f$, in the Equation (3-2), is defined below in Equation (3-4).

$$\bar{\boldsymbol{e}}_f = \bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch} + \bar{\boldsymbol{e}}^{pot} + \bar{\boldsymbol{e}}^{kin} \tag{3-4}$$

The kinetic and potential exergy terms are negligible in most of the cases studied in this thesis (excluding the hydro power cases where incoming flow of water is purely potential exergy). Some example calculations showing the negligible potential and kinetic exergy orders of magnitude can be found in Appendix D. It is also assumed that the exergy associated with magnetism and surface tension are negligible.

The molar thermomechanical exergy $\bar{\boldsymbol{e}}^{tm}$ of a stream is a measure of the maximum work, per mole, which can be produced when a flow changes from its original state to the environmental state. It is given by Equation (3-5). The molar enthalpy and the molar entropy in the environmental state are given by $\bar{h}_0$ and $\bar{s}_0$ respectively.

$$\bar{\boldsymbol{e}}_i^{tm} = \bar{h} - \bar{h}_0 - T_0(\bar{s} - \bar{s}_0) \tag{3-5}$$

The molar chemical exergy $\bar{\boldsymbol{e}}^{ch}$ of a stream is a measure of the maximum work, per mole, which can be produced when a flow changes from its environmental state to dead state. The molar chemical exergy consists of two terms – the first is the chemical exergy associated with the full reaction of each pure component present in the system with environmental components, resulting in a product consisting only of environmental components. The second term is the (negative) chemical exergy associated with the mixing of components in a system – the 'exergy of mixing'. A pure gas within the atmosphere, for example, has a much greater potential to do work than a gas mixture with a similar composition to the atmospheric environmental composition. The molar chemical exergy of an ideal mixture is given by Equation (3-6) [13].

$$\bar{\boldsymbol{e}}^{ch} = \sum_i x_i \bar{\boldsymbol{e}}_i^{ch} + \bar{R}T_0 \sum_i x_i \ln(x_i) \qquad (3\text{-}6)$$

This equation holds for all ideal mixtures of gases, as well as for all ideal solutions of liquids [14]. Hydrocarbon mixtures can generally be assumed to be ideal mixtures and as such all mixtures/solutions studied in this thesis are considered to be ideal [15].

Exergy destruction

Exergy destruction ($\dot{\mathrm{E}}_d$) is not able to be calculated directly. It is instead calculated indirectly by first determining the values of each of the other terms in Equation (3-1) (or (3-2)). In order to comply with the second law of thermodynamics, exergy destruction must always be greater than or equal to zero. It is only in a theoretical reversible system that exergy destruction is equal to zero. All real systems have entropy production, and thus exergy destruction.

3.1.3 Two-phase flow

Figure 3-2 shows a two-component, two-phase flow where x and y are the vapour and liquid fractions, respectively, for the entire stream. x_1, x_2 and y_1, y_2 are the mole fractions of each component in the vapour and liquid phases respectively.

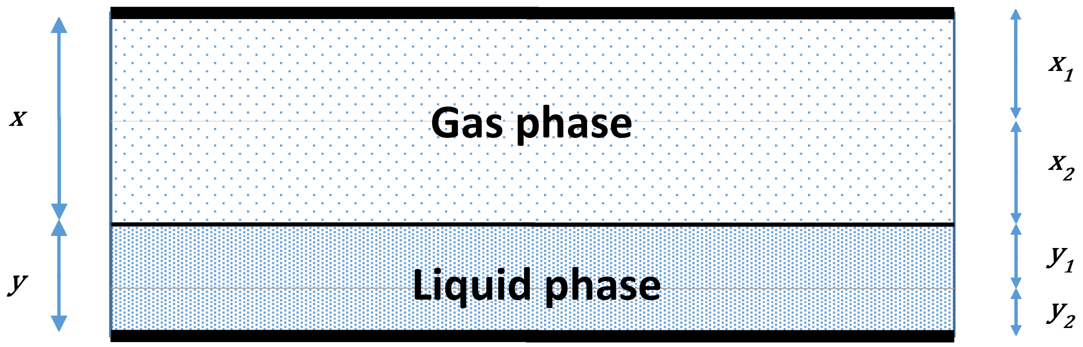

Figure 3-2 Example of a simple two-phase flow consisting of two chemical components

For two-phase flow, the chemical exergy must be calculated for each phase separately. The gas phase of a pure component has a higher chemical exergy than the liquid phase, and the mole fractions of the components are different in the gas and the liquid phases. The chemical exergy of a two-phase flow is given by Equation (3-7), where x_i and y_i are the mole fraction of the i^{th} component in the vapour phase and liquid phase, respectively.

$$\bar{\boldsymbol{e}}^{ch} = x\left(\sum_i x_i \bar{\boldsymbol{e}}_{i,g}^{ch} + \bar{R}T_0 \sum_i x_i \ln(x_i)\right) + y\left(\sum_i y_i \bar{\boldsymbol{e}}_{i,l}^{ch} + \bar{R}T_0 \sum_i y_i \ln(y_i)\right) \qquad (3\text{-}7)$$

The chemical exergy of the condensation/evaporation of a hydrocarbon ($\left(\bar{\boldsymbol{e}}_i^{ch}\right)_g - \left(\bar{\boldsymbol{e}}_i^{ch}\right)_l$) is however a relatively small fraction of the chemical exergy of the hydrocarbon. In many cases, the exergy of condensation/evaporations is also smaller than the uncertainty in the hydrocarbon chemical exergy [15]. The wellstream exergy flow rate was calculated for one of the cases, where the two-phase components were first considered as gases and then as liquids, resulting in negligible differences in total exergy flow (See Appendix A). In addition to this, the data required to calculate a hydrocarbon's chemical exergy was not available for both the gas and liquid phase, for all carbon chains from C1 – C20. For these reasons, each component is assumed to be single phase when calculating its pure chemical exergy, where this phase is the dominant phase (mole basis). The exergy of mixing terms however, still take into account the two phases present. This assumption $\left(\bar{\boldsymbol{e}}_{i,g}^{ch} = \bar{\boldsymbol{e}}_{i,l}^{ch}\right)$ allows the component chemical exergy summation terms ($\sum_i x_i \bar{\boldsymbol{e}}_i^{ch}$ and $\sum_i y_i \bar{\boldsymbol{e}}_i^{ch}$), to be taken out of each of the larger parenthesis before merging the summations, as shown in Equation (3-8).

$$\bar{\boldsymbol{e}}^{ch} = \sum_i (x \cdot x_i + y \cdot y_i)\, \bar{\boldsymbol{e}}_i^{ch} + x\left(\bar{R}T_0 \sum_i x_i \ln(x_i)\right)_g + y\left(\bar{R}T_0 \sum_i x_i \ln(y_i)\right)_l \qquad (3\text{-}8)$$

It is clear that the pure component chemical exergy's coefficient $(x \cdot x_i + y \cdot y_i)$ is equal to the component's overall molar fraction, and is thus represented by z_i in Equation (3-9).

$$\bar{\boldsymbol{e}}^{ch} = \sum_i z_i \bar{\boldsymbol{e}}_i^{ch} + x\left(\bar{R}T_0 \sum_i x_i \ln(x_i)\right)_g + y\left(\bar{R}T_0 \sum_i x_i \ln(y_i)\right)_l \qquad (3\text{-}9)$$

3.1.4 Calculation of pure component chemical exergy

The chemical exergy of the pure components is taken from the standard chemical exergy tables included in Kotas [14] when available (as is the case for all environmental components and most of the hydrocarbon components). For the hydrocarbon components not found in these tables (C17, C19 and C20) the combustion of each component with air was first set up. The general form of this reaction is given by Equation (3-10).

$$C_aH_b + \left(a + \frac{b}{4}\right)O_2 \rightarrow aCO_2 + \frac{b}{2}H_2O \qquad (3\text{-}10)$$

The standard chemical exergy of the component can then be calculated using Equation (3-11) [13], where values for $\bar{\boldsymbol{e}}^{ch}_{CO_2}$, $\bar{\boldsymbol{e}}^{ch}_{H_2O\ (l)}$ and $\bar{\boldsymbol{e}}^{ch}_{O_2}$ are taken from standard chemical exergy tables.

$$\bar{\boldsymbol{e}}^{ch}_{F} = \overline{\mathrm{HHV}}(T_0, P_0) - T_0\left[\bar{s}_F + \left(a + \frac{b}{4}\right)\bar{s}_{O_2} - a\bar{s}_{CO_2} - \frac{b}{2}\bar{s}_{H_2O\ (l)}\right](T_0, P_0) + a\bar{\boldsymbol{e}}^{ch}_{CO_2} + \left(\frac{b}{2}\right)\bar{\boldsymbol{e}}^{ch}_{H_2O\ (l)} - \left(a + \frac{b}{4}\right)\bar{\boldsymbol{e}}^{ch}_{O_2} \qquad (3\text{-}11)$$

The HHV is given by Equation (3-12). The higher heating value is used in this equation purely as this is the standard practice when calculating the chemical exergy of a fuel. The HHV is the energy released by a fuel after complete combustion of the fuel, where all of the water product is in the liquid phase.

$$\overline{\mathrm{HHV}}(T_0, P_0) = \left[\bar{h}_F + \left(a + \frac{b}{4}\right)\bar{h}_{O_2} - a\bar{h}_{CO_2} - \frac{b}{2}\bar{h}_{H_2O\ (l)}\right](T_0, P_0) \qquad (3\text{-}12)$$

Values for the absolute entropy $\bar{s}_F$ and enthalpy of formation $\bar{h}_F$ of the hydrocarbon fuel were taken from the NIST chemistry web book, a chemical property research data compilation [16]. For many of the hydrocarbon alkanes C1 – C20, enthalpy of formation and absolute entropy data are provided for both the liquid and gas phase, although not for all. For the calculation of C19 & C20, absolute entropy values were found by linear extrapolation, as shown in Appendix B. The calculation worksheet created to calculate those chemical exergies not available in Kotas is shown in Appendix C.

3.1.5 Exergy of mixing

Calculating the second term of the chemical exergy equation is a relatively straight forward process, where the mole fraction of each component is substituted into the equation. It is however, the mole fractions of each stream at standard conditions which are used here, not the actual conditions [13]. A mixture of components has less chemical exergy than an equivalent amount of the components in their pure form. This second term has thus a negative value. Many of the flows in this thesis are two-phase and care is taken in these cases to treat each phase separately i.e. the exergy of mixing is first calculated for the gas phase using x_i, and then for the liquid phase using y_i values.

3.1.6 Exergy efficiency

As discussed further in Section 2.1, there are a number of ways of defining the exergy efficiency η_{ex} , each with their advantages and disadvantages. In this thesis, the exergy efficiency is defined as the ratio of the exergy leaving the system as a useful product to the exergy entering the system, as given by Equation (3-13).

$$\eta_{ex} = \frac{\sum Exergy\ flow\ of\ useful\ products}{\sum Exergy\ flow\ into\ system} \tag{3-13}$$

Using only the terms from Equation (3-1) dealing with exergy transfer to or from the system, Equation (3-13) becomes Equations (3-14).

$$\eta_{ex} = \frac{\sum_e \dot{n}_{prod}\bar{\boldsymbol{e}}_{f,prod}}{\sum_j (1-\frac{\mathrm{T_0}}{\mathrm{T_j}})\dot{Q}_j - \left(\dot{W}_{cv} - p_0\,\frac{dV_{cv}}{dt}\right) + \sum_i \dot{n}_{in}\bar{\boldsymbol{e}}_{f,in}} \tag{3-14}$$

The useful products exiting the platform are the oil and gas flows. The high pressure water injected into the reservoir is in a sense also a useful product, but it is also a necessary mechanism for retrieving the final export products. It has thus not been classified as a product.

The exergy entering the platform differs from case to case, although the wellstream and seawater flows of exergy into the control volume are common to all cases. Section 4 presents the energy/exergy streams for each control volume.

3.2 Energy balance and efficiency

The energy rate balance is given by Equation (3-15) [13].

$$\frac{d\mathrm{E}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_{i} \dot{n}_i \bar{h}_i - \sum_{e} \dot{n}_e \bar{h}_e \tag{3-15}$$

The energy efficiency is calculated in the same fashion as the exergy efficiency, as given in Equation (3-16).

$$\eta_{en} = \frac{\sum Energy\ flow\ of\ useful\ products}{\sum Energy\ flow\ into\ system} \tag{3-16}$$

Which, when substituting in components from Equation (3-15), gives Equation (3-17)

$$\eta_{en} = \frac{\sum_e \dot{n}_{prod} \bar{h}_{prod}}{\sum_i \dot{n}_{in} \bar{h}_{in}} \tag{3-17}$$

The flow enthalpy is considered to be the lower heating value of the stream added to the 'thermal enthalpy' as defined in Equation

$$\bar{h} = \overline{LHV} + \bar{h}_{th} \tag{3-18}$$

Where the thermal enthalpy is the actual enthalpy of the stream minus the enthalpy of the same stream at reference conditions, as defined in Equation (3-19). The lower heating value is used as this is standard European practice. The LHV values calculated in HYSYS are calculated for the fuel at 15 °C.

$$\bar{h}_{th} = \bar{h} - \bar{h}_0 \tag{3-19}$$

The so-called thermal enthalpy was used in this energy analysis, as opposed to using the enthalpy value given by HYSYS, in order to achieve sensible efficiency values. HYSYS uses the IUPAC (International Union of Pure and Applied Chemistry) enthalpy reference state leading to negative enthalpies for many of the component streams. It is not possible to generate a meaningful efficiency value when some of the inlet streams have negative enthalpies. Another option is to use the LHV efficiency, as was done in the thesis's predecessor [3]. This is however a more simplistic method which does not account for the thermal or pressure energy in a stream.

The thermal energy approach was based on work done by Rian Et. Al [10]. While this method led to a non-zero energy balance differential, increasing the uncertainty marginally, it was used in in order to have energy efficiency results to compare.

3.3 Impact of reference environment on chemical exergy and LHV values

The choice of the reference environment – 1 atm. 25 °C and 60 % relative humidity – was made in order to simplify the chemical exergy calculation process. The 'standard state' at which Kotas' [14] exergy tables have been calculated has this pressure and temperature. Values from the table can thus be placed directly into Equation (3-9). This does however lead to a difference between the reference environment and the 'actual' environment specified in the simulation.

Ertesvåg [17] discusses the implication of such a difference between the actual environment and exergy reference environment. The deviation of the chemical exergy of methane was largest for the hydrocarbons considered and remained below 1 % per 10 °C difference. For the other hydrocarbons considered, the deviation decreased with increased hydrocarbon chain length. As Ertesvåg discussed in this paper, while this chemical exergy deviation due to the differences between the reference and actual environmental temperatures could be significant for single plant optimisation, it is less significant when comparing multiple plants, as is the case in this thesis. As such, although a formula is provided for 'correcting' tabulated values of standard chemical exergy of a gaseous fuel in the paper, it has not been used.

The change of a fuel's lower heating value is relatively small for changes in temperature [17] and as such the difference between the actual stream temperatures and HYSYS' LHV calculation temperature has not been taken into account.

3.4 Platform electrification and transmission losses

There are currently five operational offshore oil and gas reservoirs in the Norwegian sector being supplied with power from shore – Ormen lange, Snøhvit, Troll A, Gjøa and Valhall [19]. The electrified Goliath platform in Northern Norway is expected to be operational in 2015 [20] and other new platforms are currently being planned with onshore electrification. The biggest Norwegian offshore electrification project is the possible electrification of the Johan Sverdrup platforms and a number of other new platforms in the surrounding Utsira heights area [21].

The platforms in this thesis are assumed to be 200km from land. There are electrified platforms off the Norwegian coast which are both further from land and closer to land than this. At this distance, with plateau power demands up to around 70 MW in the full electrification cases, both AC and HVDC power transmission could be chosen [22]. In this thesis, HVDC power transfer has been assumed.

Table 3-1 shows the transmission loss data used and is based on internal Aker Solutions data. The assumption has been made that the transmission losses are constant in each case, independent of the platforms power duty. This assumption also implies that the sea cable in each case has its cross-sectional area adjusted in order for the resistance to be constant i.e. the cables in the cases with a low max power duty have a small diameter, and vice versa.

Transmission losses are dependent on many factors such as the cable cross-section, the amount of power being transmitted, the type of transmission, etc. The transmission loss percentages given in Table 3-1 are thus a starting point, and the actual transmission losses in each of the cases will vary and may well be substantially higher. The midpoints have been used initially, where a range of loss percentages has been given. A simple sensitivity analysis has been carried out, in Section 6.4, where the loss minimums and maximums have been used to find how the transmission losses influence on the overall energy and exergy efficiencies.

Table 3-1 Transmission losses between electricity production and the platform for the Norwegian route (NOR) and the German route (GER).

<table>
<tr><th>Source</th><th>Unit</th><th>NOR</th><th>GER</th></tr>
<tr><td>Transformer and AC cabling from German power plant to NorNed station in the Netherlands</td><td>%</td><td></td><td>1</td></tr>
<tr><td>AC/DC converter at NorNed station in the Netherlands</td><td>%</td><td></td><td>1</td></tr>
<tr><td>HVCD cable from the Netherlands to Norway</td><td>%</td><td></td><td>3 - 5</td></tr>
<tr><td>DC/AC converter at NorNed station in Norway</td><td>%</td><td></td><td>1</td></tr>
<tr><td>AC cabling from NorNed station to converter station onshore</td><td>%</td><td></td><td>1</td></tr>
<tr><td>Transformer and AC cabling from Norwegian power plant to converter station onshore</td><td>%</td><td>1</td><td></td></tr>
<tr><td>AC/DC converter on shore</td><td>%</td><td colspan="2">1</td></tr>
<tr><td>HVDC cable to platform and platform conversion</td><td>%</td><td colspan="2">4 - 8</td></tr>
</table>

4 Case descriptions

This section gives an overview of each of the cases. Detailed figures are included, showing the control volumes for each of the power supply options with all energy transfers to and from the control volume. Specific rate balance and efficiency equations are given after the case descriptions. The size of the arrows in the control volume diagrams does not reflect the magnitude of the energy transfer.

The design basis for the oil and gas platforms at their different operation points, as well as reservoir compositions has been included in Appendix H. For a detailed description of the process platforms under consideration, refer to the project thesis [3] preceding this thesis. Changes to the original simulations and design basis adjustments are described in Section 5.1.

4.1 Case map

An oil producing offshore platform and a gas producing offshore platform are studied at two different production points:

- Oil plateau
- Oil late-life
- Gas plateau
- Gas late-life

In addition, three different heat and power supply scenarios are studied. The different options have been labelled 2a, 2b and 2c, as in the thesis objective description:

- 2a – Gas turbine power production with heat recovery system.
- 2b – Partial electrification. Power duty supplied from land based power. Heat duty supplied by offshore gas-fired heaters.
- 2c – full electrification – Power and heat duties supplies by land based power. Electric heaters.

Three land based power options were originally planned to be a part of the study, although only two were eventually included (the reasons for which are given in Section 4.5.2):

- Norwegian hydro power
- German combined cycle gas power plant

In total, 12 different HYSYS simulation variations were used, and 28 exergy analyses were performed in Excel.

Figure 4-1 is a case map showing all of the cases on which an exergy analysis was performed. Colour coding has been used throughout the thesis as an additional reading aid. Each individual case is given a tag. For example, the late-life oil producing platform, with partial electrification supplied from a Norwegian hydro power plant has the tag ‘2b_O_ll + Nor. Hydro’. This allows for easier tabulation and description of the cases.

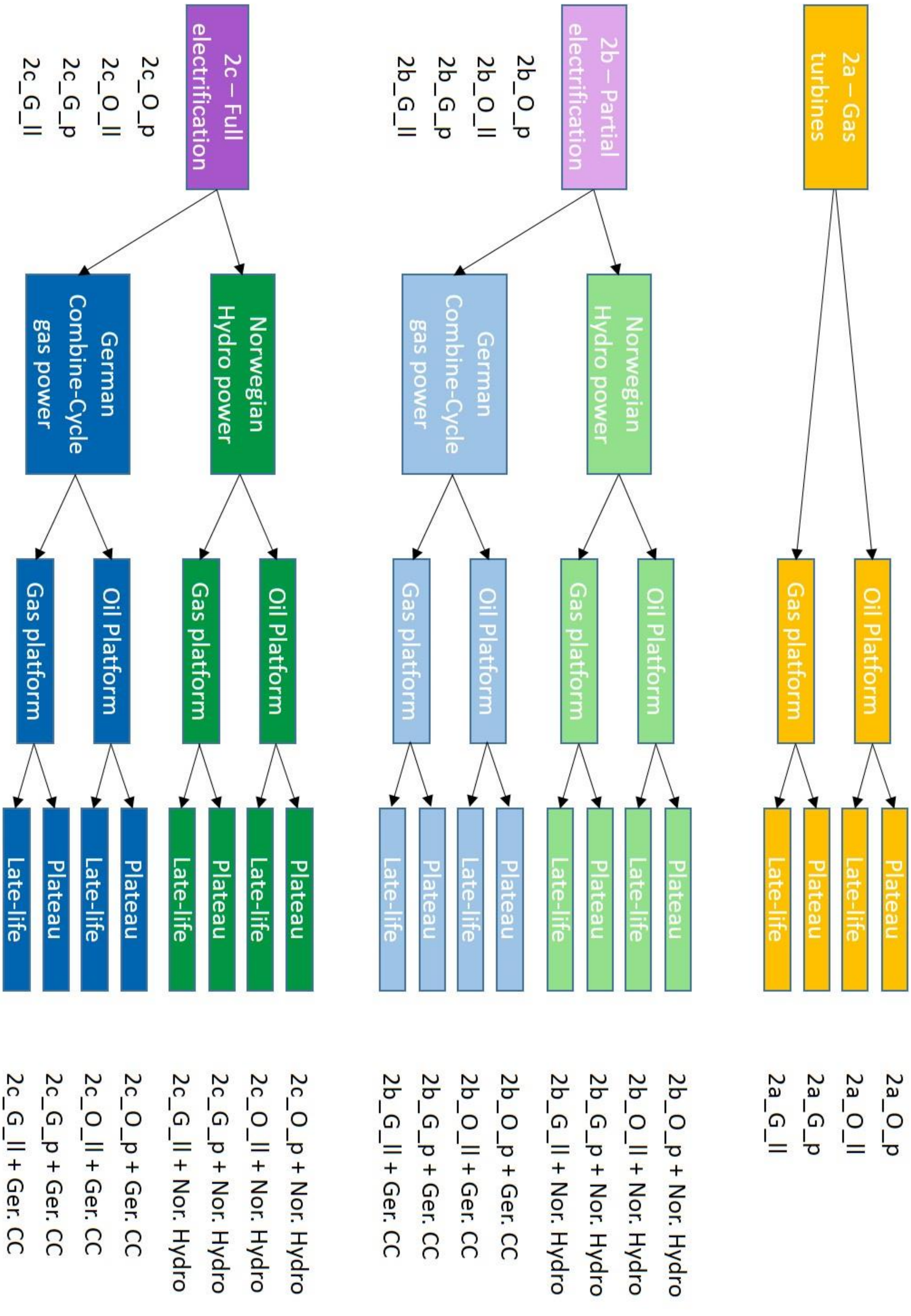

Figure 4-1 Case map showing all of the different cases on which an exergy analysis was performed

4.2 Gas turbines (2a)

In this case, a gas turbine(s) is located on the platform. The platform's power duty is provided by the gas turbine directly. The required heat is extracted from the gas turbine exhaust stream in a waste heat removal unit (WHRU). The control volume is located along the platform's exterior. Figure 4-2 illustrates the case, showing all energy/exergy flows over the control surface. Air enter the control volume to supply the gas turbine with gas, and the exhaust gas exits. The reservoir wellstream and seawater enter the process platform, while high pressure injection seawater, warm seawater used in the cooling process and high pressure produced water (from the wellstream) leave the process platform. A small amount of water from the TEG gas dehydration process also leaves the platform. The HVAC heat transfer to the platform represents heat generation on the platform due to electrical equipment, people, etc. which is subsequently carried away from the platform in the cooling water.

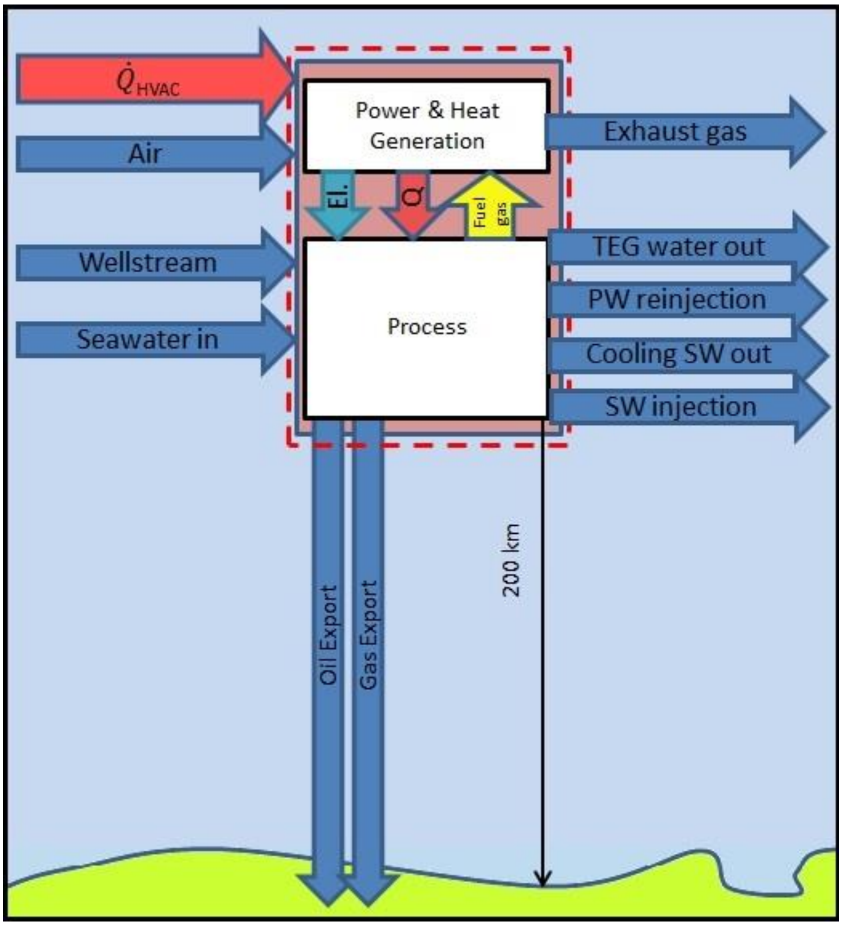

Figure 4-2 Control volume for case with gas turbine heat and power production.

4.3 Partial electrification (2b)

The partial electrification case has the same process module as in the gas turbine case. In this case however, power comes to the platform via electrical cables. Heat generation occurs in a gas-fired heater, which requires fuel gas and air and releases exhaust to the atmosphere, in a similar fashion to the gas turbine. The inlet and outlet streams in 2b are similar to those in 2a, with the addition of the electrical work flow. The control volume in Figure 4-3 does not include the power generation. The power generation and transmission control volume (found in Section 4.5) must be 'attached' to 2b's control volume in order to obtain a complete case control volume.

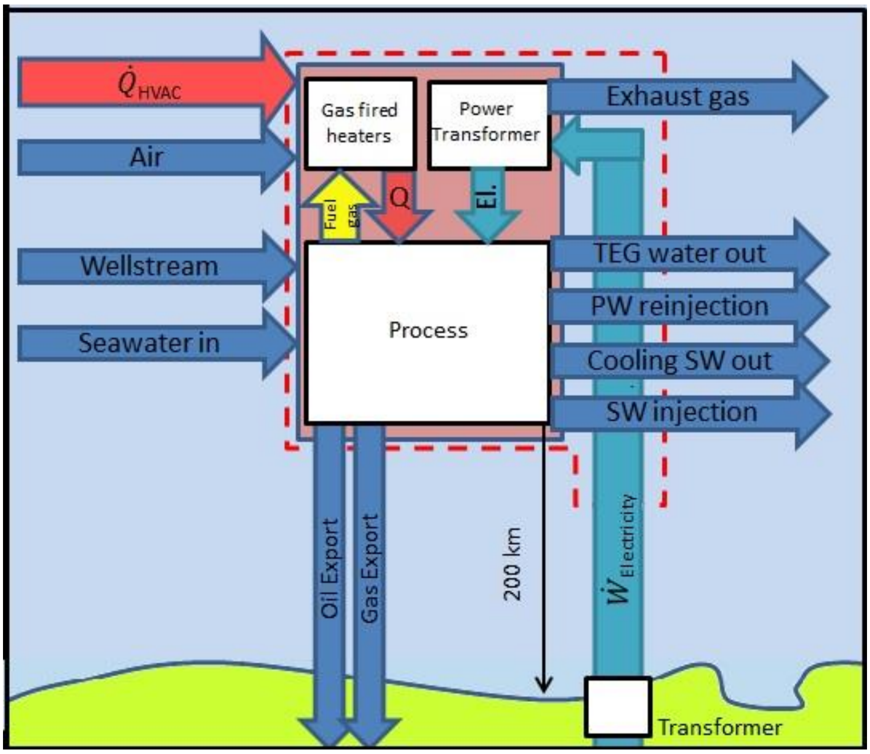

Figure 4-3 Control volume for the 2b case – partial electrification

4.4 Full electrification (2c)

Figure 4-4 shows the platform control volume for the full electrification case. All power is sourced from land, and heat is generated on the platform in electric heaters. The air and exhaust streams are no longer present. As mentioned above for the 2b cases, the 2c control volume must also be 'attached' to a power generation and transmission control volume in order to obtain a complete case.

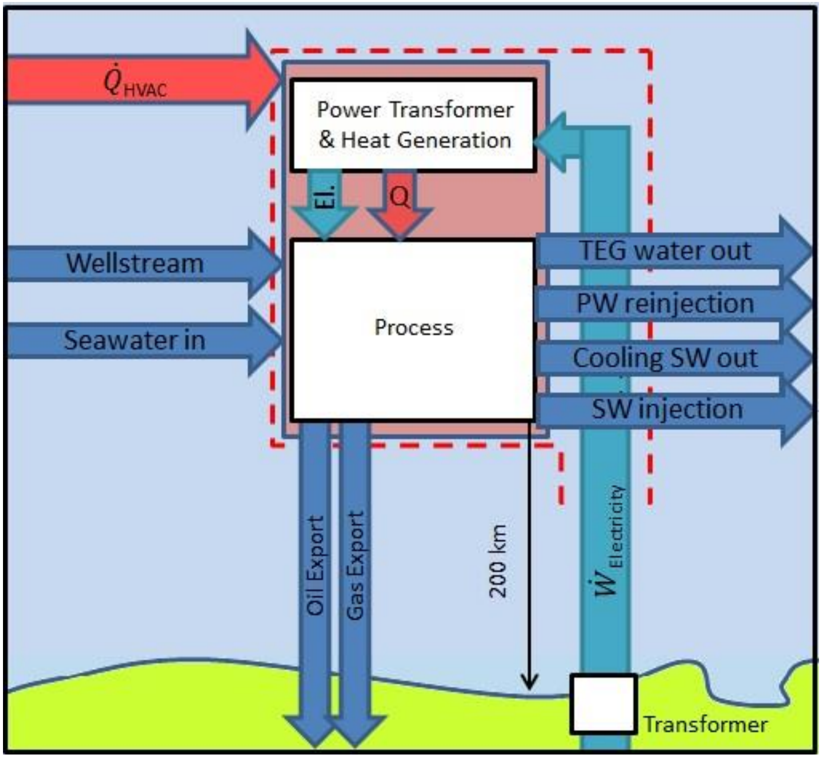

Figure 4-4 Control volume for platform with full electrification

Both the 2b and 2c scenarios have also been modelled without power generation and transmission and energy and exergy efficiencies were calculated. These 'halfway cases' can be seen in the case map (Figure 4-1) with tags such as 2b_O_p or 2c_G_ll. Simulating theses 'halfway cases' before progressing to the full cases was helpful for the purpose of quality control and in order to differentiate the effects of the different offshore heat and power generation methods from the onshore power generation and transmission.

4.5 Different electrification sources

Each of the following are possible electrification sources for the 2b and 2c cases. The hydro power plant, positioned relatively close to the platform on the Norwegian coast is chosen as a 'best case scenario' with a high efficiency, low emissions and low transmission losses. There are a number of options which could have been chosen in Germany – Coal power, solar power, etc. – but a decision was made to use a high efficiency combined cycle gas power plant. This makes for a more interesting comparison to the offshore turbines when looking at the efficiency and emission differences.

4.5.1 Norwegian hydro power

The Norwegian hydro power plant is assumed to be located 50km away from the coastline. Figure 4-5 shows the control volume for the hydro power plant and transmission infrastructure.

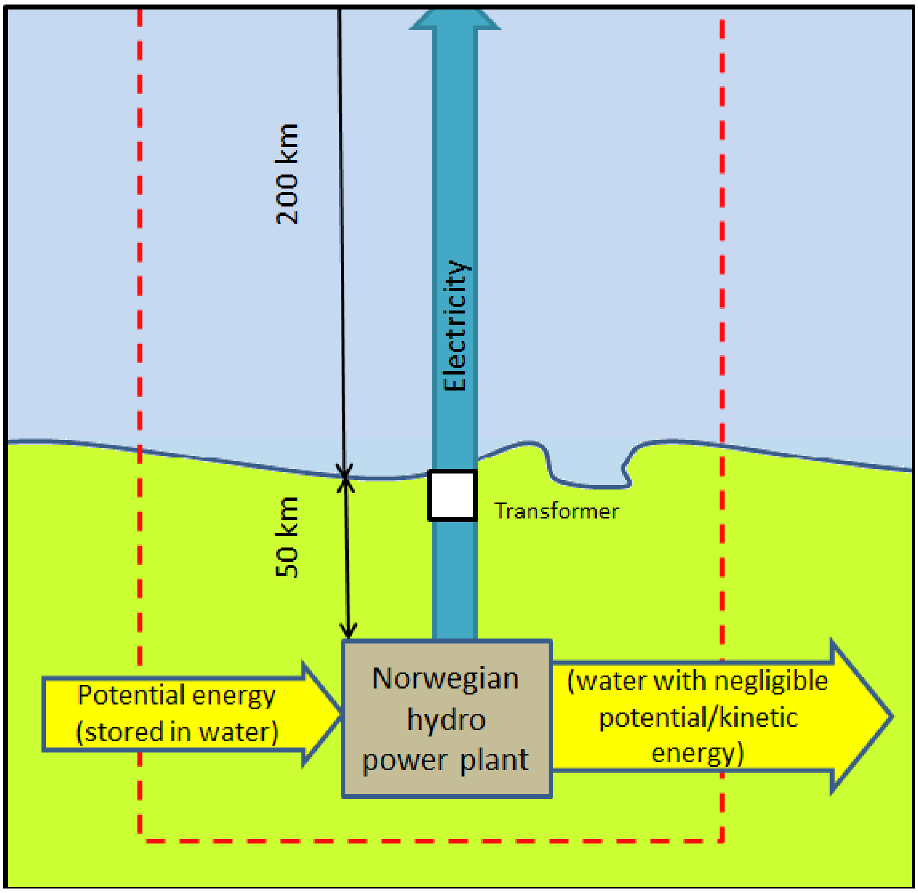

Figure 4-5 Norwegian hydro power plant control volume

The water entering the control volume is assumed to come from a large reservoir, such that the flow velocity, and thus the kinetic exergy, is negligible. The reservoir is at some height above sea level giving the mass flow potential exergy. Water exits the control volume at the draft tube exit after having passed through the turbine, where the water velocity and kinetic exergy are again assumed to be negligible. This point is assumed to be at sea level, meaning that the mass flow has no potential exergy. The chemical and thermomechanical exergy of the water has been ignored here.

The hydro power plant's efficiency is set to be 85 % based on actual plant efficiencies ranging from around 80 – 90 % [23, 24]. Using the required plant electricity output (taking power transmission losses into account) the amount of potential energy required in the water stream can be calculated. Potential energy can be completely converted to work and is thus equal to potential exergy.

4.5.2 Norwegian combined cycle gas power plant

This case has been consciously excluded from the analysis. The reason for this is that the results for this case would lie between those of the other two electrification options (assuming of course that the German Norwegian combined cycle gas power plants are the same). The only difference between this option and the German variant would be the higher transmission losses for the German plant.

4.5.3 German Combined cycle gas power plant (CCGT)

Figure 4-6 shows the control volume for the German combined cycle power plant and the power transmission infrastructure. This control volume is added to 2b or 2c's control volume in the cases where their electrical power source is the German power plant.

The figure shows a simplified version of the power transport from Germany to the Norwegian coast. See Table 3-1 for a more detailed description.

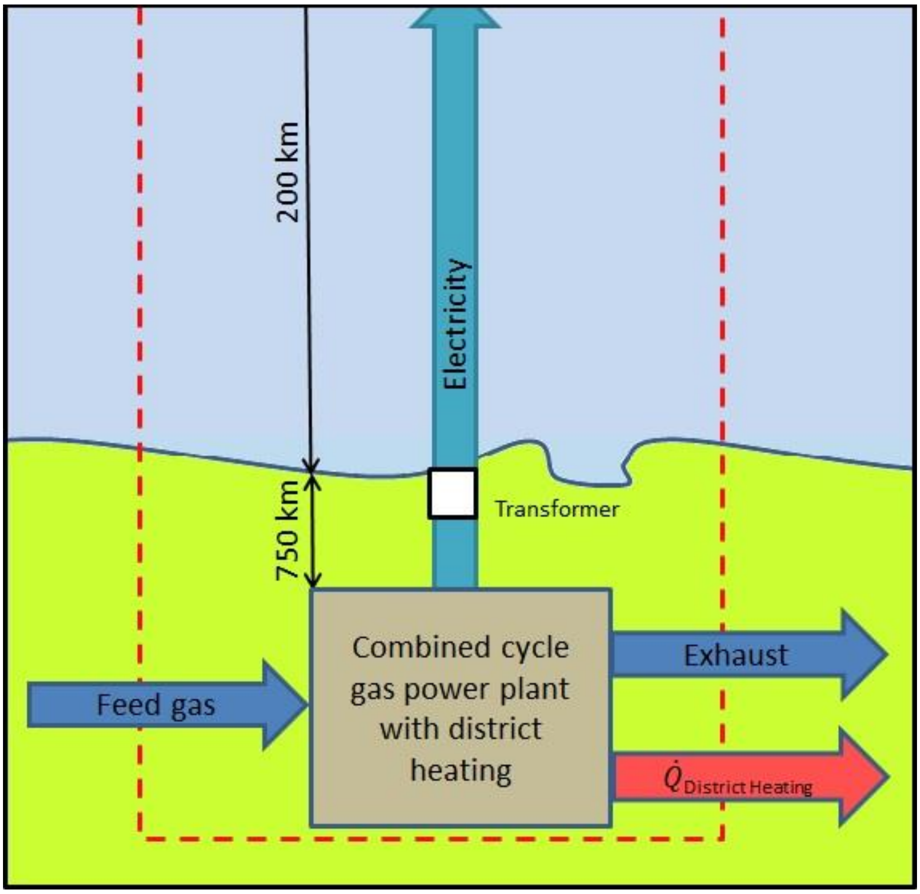

Figure 4-6 Control volume for German combine cycle power plant

The inlet to the combined cycle gas power plant is assumed to be a fuel gas stream, with the same composition as the gas exported from the gas platform. In addition to power, this plant is assumed to produce heat which is exploited in a district heating system. The district heating is considered one of the systems 'useful products'. A loss from the power plant is the heat contained in the exhaust gas after the district heating heat exchanger. The control volume is assumed to pass directly though the district heating heat exchanger such that this energy leaves the control volume as a heat transfer rather than being contained in a mass stream. This heat transfer is assumed to occur at 150 °C [25].

The combined cycle gas power plant is assumed to be a modern, efficient plant, with a thermal efficiency of 60 % (LHV basis). The district heating system attached to the power plant increases the energy yield to 85 % of the original inlet stream (also LHV basis). These figures are based on modern projects being planned/built in Germany currently [26-28]. The excess air ratio of the gas turbine is set at 3.

4.6 Rate balances and efficiencies

This section gives the specific rate balances and the exergy efficiencies for all cases. The equations given here are case specific versions of Equations (3-2), (3-14), (3-15) and (3-17). Whilst technically not new equations, they have been given equations numbers for readability.

4.6.1 Gas turbines (2a)

The exergy and energy rate balances for the 2a cases are given in equations (4-1) and (4-2) respectively.

$$0 = \left(\frac{\mathrm{T_0}}{\mathrm{T_{HVAC\ avg}}} - 1\right)\dot{Q}_{HVAC} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \dot{\mathbf{E}}_d \tag{4-1}$$

$$0 = \dot{Q}_{HVAC} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) \tag{4-2}$$

The exergy and energy efficiencies for the 2a cases are given by Equation (4-3) and (4-4) where the ‘well’, ‘SW’ and ‘air’ subscripts represent the wellstream, seawater and gas turbine air mass flows respectively.

$$\eta_{ex} = \frac{\dot{n}_{Oil}\bar{\boldsymbol{e}}_{f,oil} + \dot{n}_{Gas}\bar{\boldsymbol{e}}_{f,Gas}}{\left(\frac{\mathrm{T_0}}{\mathrm{T_{HVAC\ avg}}} - 1\right)\dot{Q}_{HVAC} + \dot{n}_{well}\bar{\boldsymbol{e}}_{f,well} + \dot{n}_{SW}\bar{\boldsymbol{e}}_{f,SW} + \dot{n}_{air}\bar{\boldsymbol{e}}_{f,air}} \tag{4-3}$$

$$\eta_{en} = \frac{\dot{n}_{Oil}\bar{h}_{oil} + \dot{n}_{Gas}\bar{h}_{Gas}}{\dot{Q}_{HVAC} + \dot{n}_{well}\bar{h}_{well} + \dot{n}_{SW}\bar{h}_{SW} + \dot{n}_{air}\bar{h}_{air}} \tag{4-4}$$

4.6.2 Norwegian hydro power (+ 2b and 2c)

The rate balances for the 2b + Nor. hydro and 2c + Nor. hydro cases are only be differentiated by the energy/exergy flows associated with the gas-fired burner. As such the balances will have the same general terms. The exergy and energy rate balances are given in Equations (4-5) and (4-6) respectively. The electrical work term does not appear in these equations, as the power transmission occurs internally in the control volume. Notice also the addition of the potential energy/exergy term $\dot{\mathrm{E}}_{PE}$.

$$0 = \left(\frac{\mathrm{T}_0}{\mathrm{T}_{\mathrm{HVAC}}} - 1\right)\dot{Q}_{HVAC} + \dot{\mathbf{E}}_{PE} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \dot{\mathbf{E}}_d \tag{4-5}$$

$$0 = \dot{Q}_{HVAC} + \dot{\mathrm{E}}_{PE} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) \tag{4-6}$$

For the 2b + Nor. hydro cases, the exergy and energy efficiencies are given by Equations (4-7) and (4-8).

$$\eta_{ex} = \frac{\dot{n}_{Oil}\bar{\boldsymbol{e}}_{f,oil} + \dot{n}_{Gas}\bar{\boldsymbol{e}}_{f,Gas}}{\left(\frac{\mathrm{T}_0}{\mathrm{T}_{\mathrm{HVAC\ avg}}} - 1\right)\dot{Q}_{HVAC} + \dot{n}_{well}\bar{\boldsymbol{e}}_{f,well} + \dot{n}_{SW}\bar{\boldsymbol{e}}_{f,SW} + \dot{n}_{air}\bar{\boldsymbol{e}}_{f,air} + \dot{\mathbf{E}}_{PE}} \tag{4-7}$$

$$\eta_{en} = \frac{\dot{n}_{Oil}\bar{h}_{oil} + \dot{n}_{Gas}\bar{h}_{Gas}}{\dot{Q}_{HVAC} + \dot{n}_{well}\bar{h}_{well} + \dot{n}_{SW}\bar{h}_{SW} + \dot{n}_{air}\bar{h}_{air} + \dot{\mathrm{E}}_{PE}} \tag{4-8}$$

The 2c + Nor. hydro cases' exergy and energy efficiencies are given by Equations (4-9) and (4-10) respectively.

$$\eta_{ex} = \frac{\dot{n}_{Oil}\bar{\boldsymbol{e}}_{f,oil} + \dot{n}_{Gas}\bar{\boldsymbol{e}}_{f,Gas}}{\left(\frac{\mathrm{T}_0}{\mathrm{T}_{\mathrm{HVAC\ avg}}} - 1\right)\dot{Q}_{HVAC} + \dot{n}_{well}\bar{\boldsymbol{e}}_{f,well} + \dot{n}_{SW}\bar{\boldsymbol{e}}_{f,SW} + \dot{\mathbf{E}}_{PE}} \tag{4-9}$$

$$\eta_{en} = \frac{\dot{n}_{Oil}\bar{h}_{oil} + \dot{n}_{Gas}\bar{h}_{Gas}}{\dot{Q}_{HVAC} + \dot{n}_{well}\bar{h}_{well} + \dot{n}_{SW}\bar{h}_{SW} + \dot{\mathrm{E}}_{PE}} \tag{4-10}$$

4.6.3 German combined cycle gas power (+ 2b and 2c)

As above, the rate balances for the 2b + Ger. CC and 2c + Ger. CC cases will be similar. The energy and exergy rate balances for these cases are given in Equations (4-11) and (4-12) respectively. Notice the introduction of the district heating heat transfer $\dot{Q}_{DH}$. The HVAC heat transfer occurs below the reference temperature of 25 °C, whilst the district heating heat transfer occurs above the reference temperature, hence the difference in the terms (see Equation (3-3) in Section 3.1.2).

$$0 = \left(\frac{\mathrm{T_0}}{\mathrm{T_{HVAC}}} - 1\right)\dot{Q}_{HVAC} + \left(1 - \frac{\mathrm{T}_{DH}}{\mathrm{T_0}}\right)\dot{Q}_{DH} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \dot{\mathbf{E}}_d \qquad (4\text{-}11)$$

$$0 = \dot{Q}_{HVAC} + \dot{Q}_{DH} + \sum_{in}\dot{n}_{in}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) - \sum_{out}\dot{n}_{out}(\bar{\boldsymbol{e}}^{tm} + \bar{\boldsymbol{e}}^{ch}) \qquad (4\text{-}12)$$

The exergy and energy efficiencies of the 2b + Ger. CC cases are given in Equations (4-13) and (4-14) respectively, where 'Feed' stands for the power plant's inlet feed gas flow.

$$\eta_{ex} = \frac{\dot{n}_{Oil}\bar{\boldsymbol{e}}_{f,oil} + \dot{n}_{Gas}\bar{\boldsymbol{e}}_{f,Gas} - \left(1 - \frac{\mathrm{T}_{DH}}{\mathrm{T_0}}\right)\dot{Q}_{DH}}{\left(\frac{\mathrm{T_0}}{\mathrm{T_{HVAC\,avg}}} - 1\right)\dot{Q}_{HVAC} + \dot{n}_{well}\bar{\boldsymbol{e}}_{f,well} + \dot{n}_{SW}\bar{\boldsymbol{e}}_{f,SW} + \dot{n}_{air}\bar{\boldsymbol{e}}_{f,air} + \dot{n}_{Feed}\bar{\boldsymbol{e}}_{f,Feed}} \qquad (4\text{-}13)$$

$$\eta_{en} = \frac{\dot{n}_{Oil}\bar{h}_{oil} + \dot{n}_{Gas}\bar{h}_{Gas} - \dot{Q}_{DH}}{\dot{Q}_{HVAC} + \dot{n}_{well}\bar{h}_{well} + \dot{n}_{SW}\bar{h}_{SW} + \dot{n}_{air}\bar{h}_{air} + \dot{n}_{Feed}\bar{h}_{Feed}} \qquad (4\text{-}14)$$

The energy and exergy efficiencies of the 2c + Ger. CC cases are given in Equations (4-15) and (4-16) respectively.

$$\eta_{ex} = \frac{\dot{n}_{Oil}\bar{\boldsymbol{e}}_{f,oil} + \dot{n}_{Gas}\bar{\boldsymbol{e}}_{f,Gas} - \left(1 - \frac{\mathrm{T}_{DH}}{\mathrm{T_0}}\right)\dot{Q}_{DH}}{\left(\frac{\mathrm{T_0}}{\mathrm{T_{HVAC\,avg}}} - 1\right)\dot{Q}_{HVAC} + \dot{n}_{well}\bar{\boldsymbol{e}}_{f,well} + \dot{n}_{SW}\bar{\boldsymbol{e}}_{f,SW} + \dot{n}_{Feed}\bar{\boldsymbol{e}}_{f,Feed}} \qquad (4\text{-}15)$$

$$\eta_{en} = \frac{\dot{n}_{Oil}\bar{h}_{oil} + \dot{n}_{Gas}\bar{h}_{Gas} - \dot{Q}_{DH}}{\dot{Q}_{HVAC} + \dot{n}_{well}\bar{h}_{well} + \dot{n}_{SW}\bar{h}_{SW} + \dot{n}_{air}\bar{h}_{air} + \dot{n}_{air}\bar{h}_{air} + \dot{n}_{Feed}\bar{h}_{Feed}} \qquad (4\text{-}16)$$

4.7 Summary of efficiencies and transmission losses for the electrification cases

Figures Figure 4-7 and Figure 4-8 show examples of the energy losses between each of the power plant options and the platform process. In each figure, an example platform with a heat duty of 25 MW and a power duty of 25 MW is supplied with power from either a German combined cycle power plant or a Norwegian hydro power plant.

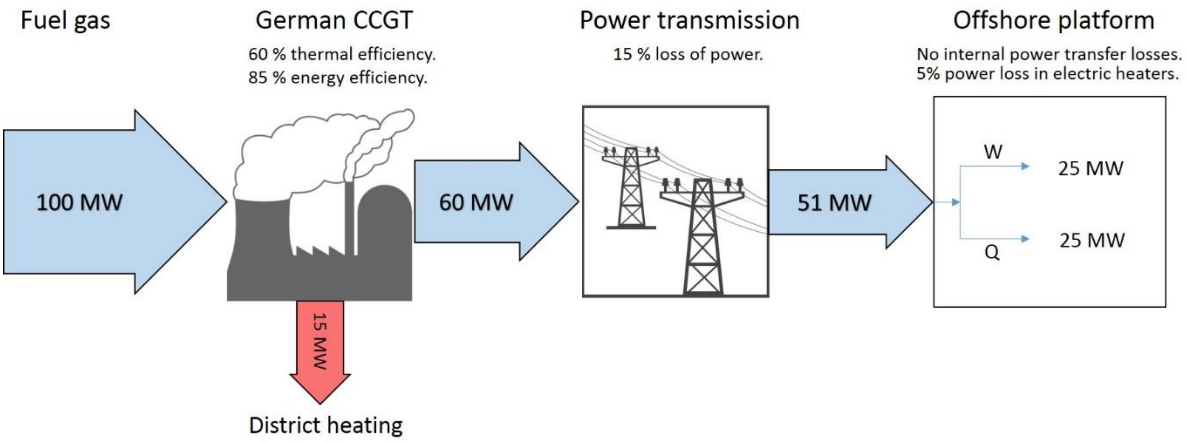

Figure 4-7 Energy losses from German CCGT power plant inlet to platform process

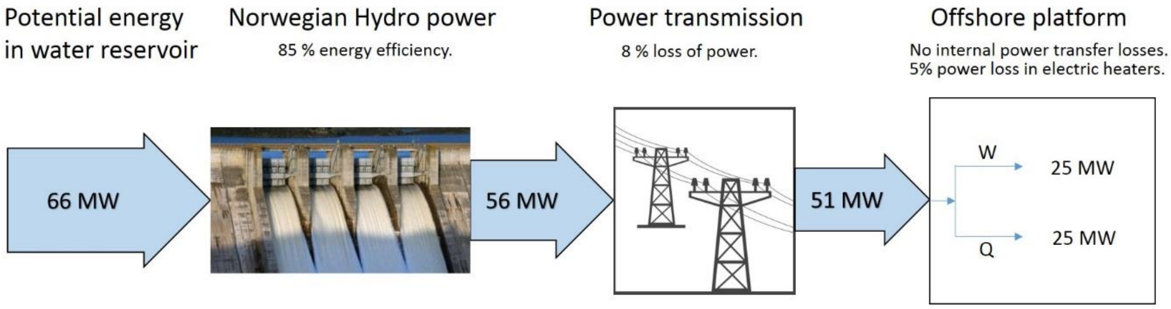

Figure 4-8 Energy losses from Norwegian hydro power plant inlet to platform process

5 Method

The exergy analysis is based primarily on data calculated in the process simulation software Aspen HYSYS in addition to chemical exergy data from Kotas [14]. Mass and energy flows are calculated in HYSYS for the process platform, offshore gas turbines and gas-fired heaters as well as for the German combined cycle gas power plant. The Peng-Robinson equation of state is used in all simulations. See the project thesis preceding this thesis for more information regarding the simulation process [3].

5.1 HYSYS use

Each of the cases in Figure 4-1, had its process platform and gas turbine/gas burner simulated in HYSYS. Four original HYSYS simulations – oil plateau, oil late-life, gas plateau and gas late-life - were created as part of the project thesis preceding this thesis. It was however necessary to initially make a number of adjustments to these original simulations, before continuing to the specific case adjustments.

The first simulation adjustments were required as a result of changes in the design basis. These changes were made in order to attain more 'typical' platforms. These changes included a new oil reservoir chemical composition, changes to the HVAC duty, non-process heating and drilling duties and switching from platform storage to pipeline transport of all oil to shore. See Appendix J and Appendix K for the oil reservoir compositions and screenshots of the HYSYS files.

To better reflect actual pressure loss in the platform heaters/coolers, different pressure losses have been used for different pressure levels in the gas recompression train. For $P < 2$ bar, $\Delta P = 0.3$ bar, for $2 < P < 7$ bar, $\Delta P = 0.5$ bar and for $P > 23$ bar, $\Delta P = 1$ bar.

Case adjustments

Once the four base simulations were amended, copies were made of each of the four simulations. Four simulation copies were made for the 2b case, in which the gas turbine was exchanged for a gas-fired heater. Four simulation copies were made for the 2c case in which the gas turbine/gas-fire heater was removed completely. A separate simulation was created for the German CCGT. This resulted in a total of 13 HYSYS simulations which could then export data to Microsoft Excel for the exergy analyses.

The steps involved with amending the simulations are explained further below.

Environmental streams

In order to calculate the thermomechanical exergy and exergy of mixing for each of the streams entering the control volume, the enthalpy and entropy of equivalent streams in the environmental state were required. As such, all open mass flows in the simulations have a duplicate stream, with the same component flow rate, but at 1 atm. and 25° C. A HYSYS 'balance' tool ensure that the duplicate stream's component flow rate follows that of the actual stream.

Gas turbine simulation

The gas turbines were originally (in [3]) simulated by fitting trend lines to GE data for fuel consumption, exhaust gas temperature and flow rate, and power output at varying loads.

These trend line equations were contained in a HYSYS spreadsheet which acted as the gas turbine simulation. This led, however, to control volume mass and energy balances issues. To avoid this, the trend lines for the GE fuel gas energy consumption, air mass flow and power output were still used, but in combination with a Gibbs reactor to attain exhaust gas temperature and mass flow rate. A Gibbs reactor simulates the reaction where the Gibbs free energy is minimised and does not require stoichiometric data for the reaction. The HYSYS calculations gave results which were acceptably close to the GE data for the exhaust gas temperature, but which also ensured energy and mass balances that summed to zero. The gas turbine setup in HYSYS can be seen in Figure 5-1. In addition to the trend lines calculated in the project thesis [3], the fuel gas mass flow data from GE was tabulated and a trend line was found in order to calculate the required fuel gas for the gas turbine, see Appendix L.

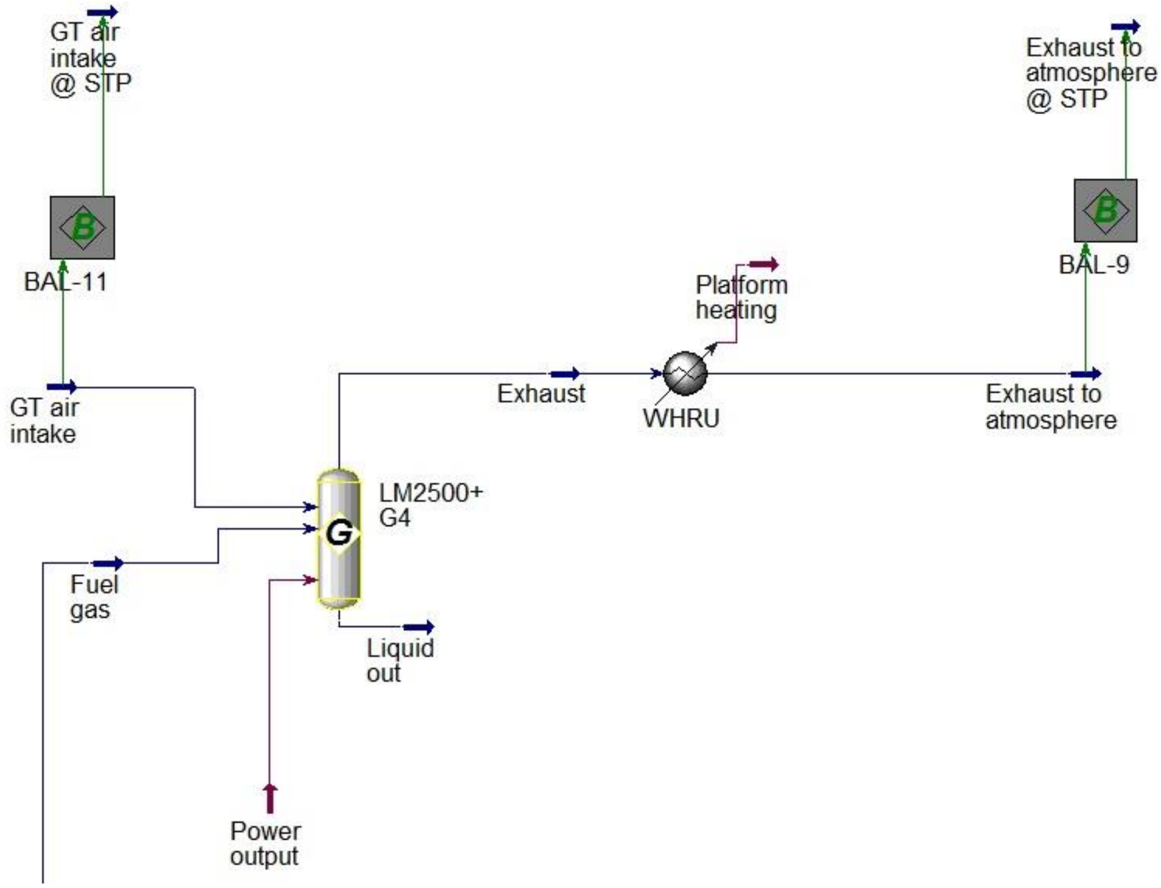

Figure 5-1 Gas turbine simulation in HYSYS

Gas-fired heater simulation

The gas-fired heaters were simulated in HYSYS using a Gibbs reactor once again in a similar configuration to that shown in Figure 5-1. A copy of the gas-fired heater was set up separately in each simulation in order to calculate stoichiometric combustion for the given fuel gas flow rate. The actual combustion was simulated with an excess air ratio of 1.1. The combustion products leave the burner with temperatures ranging from 1835 -1885 °C and are reduced to 140 °C in the heat exchanger that follows. The fuel gas flow rate was adjusted in order to obtain the platform heat duty from the heat exchanger. An iterative process was used here.

German combined-cycle power plant

The German combined cycle gas power plant was simulated in a separate HYSYS simulation. Once again, a Gibbs reactor was used to calculate the properties of the combustion products. Output data from one simulation, with different inputs, was used to calculate the energy and exergy flows for the German CCGT power plant in each of the eight applicable cases. The simulation power production was adjusted to the power requirements (taking into account transmission losses) of each case in which the German power option was included. Each of the power production points required the calculation of the air flow and fuel flow which would give the required power. Exergy and energy flow rates from the CCGT plant were then exported to the 2b + Ger. CC and 2c + Ger. CC exergy analyses.

CO_2 emission calculation

CO_2 emission data was obtained from the Gibbs reactor gas outlet streams in HYSYS for the gas turbines, gas-fire heaters and German CCGT power plant. This data was then exported to the relevant energy/exergy worksheets and yearly emission rates were calculated based on the assumption that the plants are in operation 95 % of the time.

5.2 Data import

HYSYS Stream reporter is used to import stream data from HYSYS to Excel. It is an Excel program which can detect a running HYSYS simulation and allows the user to choose certain streams and properties of those streams to be imported. Table 5-1 gives an overview of the properties imported from HYSYS for each for the streams crossing the control volume.

Table 5-1 HYSYS properties imported into Excel for efficiency and emission calculations.

Property	Specific aspect
Temperature	
Pressure	
Molar flow	Overall
Molar flow	Vapour
Molar flow	Combined liquid
Molar enthalpy	
Molar entropy	
Lower heating value	
Component molar fraction	Overall
Component molar fraction	Combined liquid
Component molar fraction	Vapour

5.3 Excel

Each case (2b_O_ll + Nor. Hydro, etc.) was assigned a separate excel file and multiple worksheets were created in each file – raw HYSYS stream data (from HYSYS stream reporter), chemical exergy calculations, component chemical exergy library, and finally an exergy efficiency worksheet. In the exergy calculation worksheet, chemical exergies are first calculated for each component in each stream, using the first term of Equation (3-9) and linking to the chemical exergy library worksheet. See Appendix M for more information about the chemical exergy library. In the same sheet, the exergy of mixing contribution from every component in each stream is also calculated using the latter terms in Equation (3-9) and totalled. The final worksheet included calculations regarding those parts of the control volume not simulated in HYSYS (E.g. power transmission, hydro power plant, etc.) as well as finding the thermomechanical exergies and finally calculating overall energy and exergy efficiencies.

An excel file was established for each case variant. With four platform simulations for each power supply case and seven power supply cases this resulted in a total of 28 different scenarios.

Each of these 28 files was linked to an overview worksheet displaying platform duties, energy and exergy efficiencies, exergy lost and destroyed, CO_2 production and energy and mass balances. This overview sheet simplified the process of sorting, comparing and graphing the data.

5.4 Quality control

A number of quality control checks were made after the first exergy efficiency worksheets were established. This turned out to be a relatively time consuming process due to the complexity of both the HYSYS simulations and the Excel worksheets. A number of errors were found in both the HYSYS and Excel spreadsheets, highlighting the importance of this process. It also lead to the decision to model the gas turbines differently, as discussed in Section 5.1.

Mass balance

Mass balance checks were performed continuously throughout the HYSYS simulation period, ensuring that all of the platform inlets and outlets were taken into account in the HYSYS spreadsheets. The recycle loop logical in HYSYS was used to model flow lines on the process platform which return to a previous processing stage (e.g. from the gas recompression train back to the separation train). In order to aid calculation convergence, different stream properties are allowed certain tolerances. The flow rate tolerance in the recycle loops had to be reduced in order to reduce the overall mass balance differential for the platform. The largest mass balance differential in any of the cases was kept to below 0.0004 % of the inlet mass flow rate. See Appendix E for all of the mass and energy balances.

Energy balance

The energy balance was checked by summating all of the inlet and outlet terms in Equation (3-15) and finding the difference. For the energy balance to be true, the difference should be equal to zero according to the first law of thermodynamics. This check was the step that required the most time. The energy balance was first calculated in Excel and the differential was found to be a non-zero, up to a few tenths of a percent of the inlet energy flow. This is a relatively large amount of energy when considered in light of the large amounts of energy flowing through the system. The same process was then carried out within HYSYS to ensure the error did not occur in the export process. When the same error showed up here the next step was to try to isolate the problem to a specific part of the simulation by calculating the energy balance for each of the main processes (separation, compression, etc.). Part of the error was located to the gas turbine resulting in an adjustment to the way the turbine was simulated, as discussed in Section 5.1. In addition to the energy contained in the mass streams, is the energy flow to and from heat exchangers, pumps, compressors, TEG unit, etc. all of which are summated internally in HYSYS. It is here that the remaining error was located. When all errors were corrected, the energy balance differentials were kept below 0.00005 % of the inlet energy.

It was this quality control process which led to the discovery of issues with the 'thermal energy' in Equation (3-19), used to calculate energy efficiencies. The thermal energy balance gives an energy differential which is always negative when thermal energy out is subtracted from thermal energy in (See Appendix E). The differential ranges from 0.029 – 0.258 % of the inlet thermal energy, with an average of 0.094 %. This value would appear to be relatively large in light of the small energy efficiency variations. It is however not believed to be a significant factor. The thermal energy balance differential appears due to the subtraction of each streams environmental enthalpy from its actual enthalpy. The differential is thus a consequence of all of the inlet streams which would indicate that the error is also spread over all of the streams, thus having a minimal effect on the energy efficiency.

The exergy balance is unable to be checked in the same way as the energy balance due to the non-zero exergy destruction term which cannot be measure directly. The streams and power transfers used in calculating the exergy terms are identical to those used when calculating the energy (albeit using different stream properties). By first establishing that the energy balance is in order, the results of the exergy term calculations become more trustworthy.

One simple check which can be performed on the exergy results is whether the exergy destruction term is positive. If it is negative, exergy is being produces, breaking the second law of thermodynamics. This simple check lead to the early discovery of an error in the calculation of the exergy of mixing term.

Literature comparison

The gas reservoir composition used in this thesis is the same as that which was used in Rian's exergy analysis [5]. This has given a unique opportunity to compare the energy and exergy calculation methods. Appendix N shows the specific energy/exergy (i.e. mass basis) comparisons between the 2a_G_p case and Rian's wellstream. The 2a_G_p case's specific chemical exergy was just over 1 % greater than Rian's, whilst its specific LHV was under 1 % greater than Rian's. These values suggest that the calculations have been carried out in a similar fashion. The thermomechanical exergy and 'thermal energy' for 2a_G_p were both about 25 % greater than Rian's. This is due to the temperature and pressure differences in the wellstreams.

5.5 Assumptions

A number of new assumptions have been made regarding the simulation, differing from those in the project thesis. The exergy calculation process also involved many assumptions, some of which have been mentioned in Section 3.1, other of which are omitted here and included in a more comprehensive table of assumptions in Appendix O.

The kinetic and potential energies/exergies of all platform and combined cycle power plant flows are considered to be negligible, see Appendix D for examples. The platform is also considered to be a black box. All heat loss from the equipment is considered negligible and the only heat entering or leaving the platform is in the mass streams. There is however one exception to this and that is the HVAC cooling. To remove heat from electrical equipment, living quarters, etc. heat must be transferred into the cooling seawater by mean of air conditioning for example. For the cooling water stream in HYSYS, this appears as a heat source within the control volume. It is thus treated as if it were a heat transfer to the control volume when calculating the exergy in the energy transfer.

While power transmission losses are considered for all long distance transport, and heat losses are considered for the electric heating process, internal platform power transmission losses have not been considered. The efficiencies of the platform heat exchangers (WHRU and gas-fired heater HX) have not been taken into account in any of the HYSYS simulations and complete heat transfer has thus been assumed.

When calculating the yearly CO_2 emissions from the platform and German combined cycle gas power plant, a production uptime of 95% is assumed, implying 347 production days per year.

6 Results and Discussion

This section presents an overview of the calculated results. Additional overview material is available in Appendices Appendix E, Appendix F and Appendix G.

6.1 Power, heating and cooling duties

The power, heating and cooling duties and production rates for each of the platforms' operation points, with different power supply options, are tabulated in Appendix P. A detailed overview of all of the consumers on each platform is included in the preceding project thesis [3]. Although some changes have been made to the design basis since the project thesis, the platform duties are still relatively similar. The qualitative comparisons and conclusions made in the project thesis regarding the platform duty differences still hold true.

The 2a, 2b and 2c duties for each platform operation points are naturally relatively similar. The differences that do exist come about in the final gas compression and export stage. Variations in the power supply option change the mass flows through the HP export compressor, fuel gas heater, and export cooler, leading to the small variations in the duties. In case 2a, a considerable amount of the export gas is diverted, prior to export compression, heated and then used as fuel gas in the gas turbine. In case 2b, a similar setup diverts a smaller amount of fuel gas to the gas-fired heaters. In case 2c, no fuel gas is diverted resulting in the highest mass flow through the HP export compressor and export cooler.

Figure 6-1 shows the platform power duties for 2a, 2b and 2c.

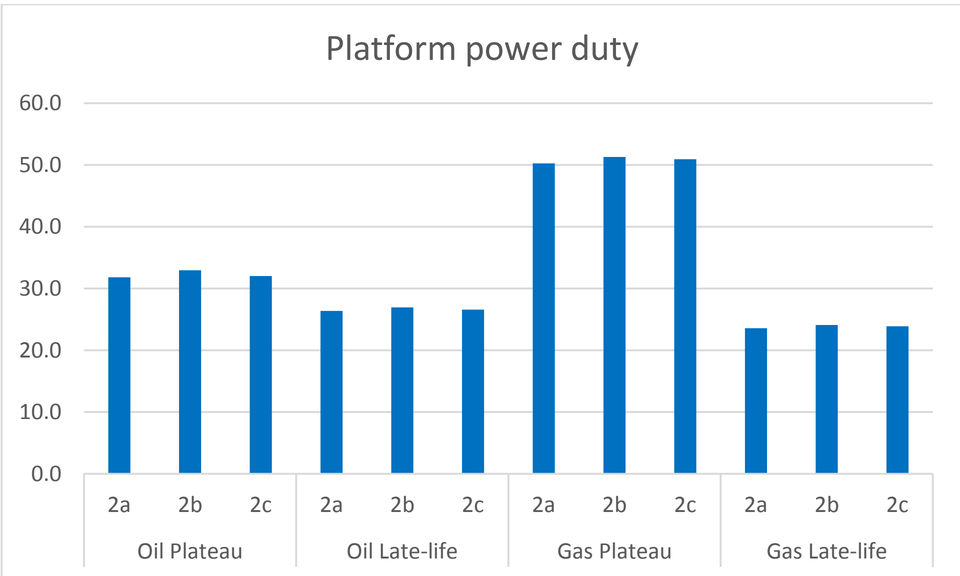

Figure 6-1 Platform power duties for the three main power supply alternatives at each operating point.

Comparing cases 2b and 2c to 2a (for all platform operation points), we can see that the 2b and 2c cases have a higher power duty. This is due to the increased mass flow rate through the HP export compressor. The HP export compressor in 2c requires more power than in 2b due to the higher mass flow rate; 2b has a higher overall power duty however, due to the addition of an air compressor in connection with the gas-fired heaters.

Figure 6-2 shows the platform heat duties for 2a, 2b and 2c.

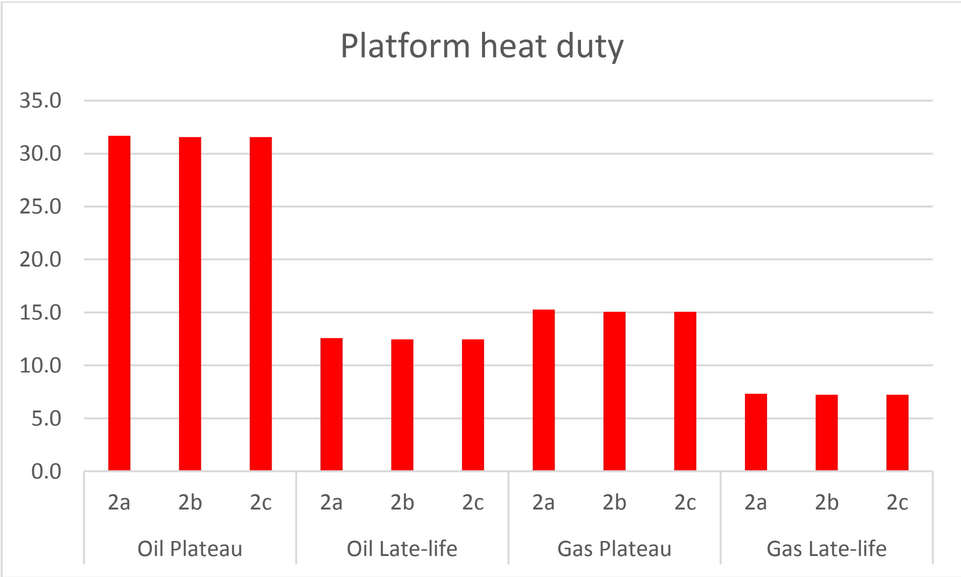

Figure 6-2 Platform heat duties for the three main power supply alternatives at each operating point.

The heating duty in 2a is higher than in 2b and 2c due to the gas turbine requirement of preheated fuel gas. Pre-heating of the gas-fired heater's fuel gas (2b) was not employed, resulting in the same heat duties for the 2b and 2c cases, at each operation point.

Figure 6-3 shows the platform cooling duties for 2a, 2b and 2c.

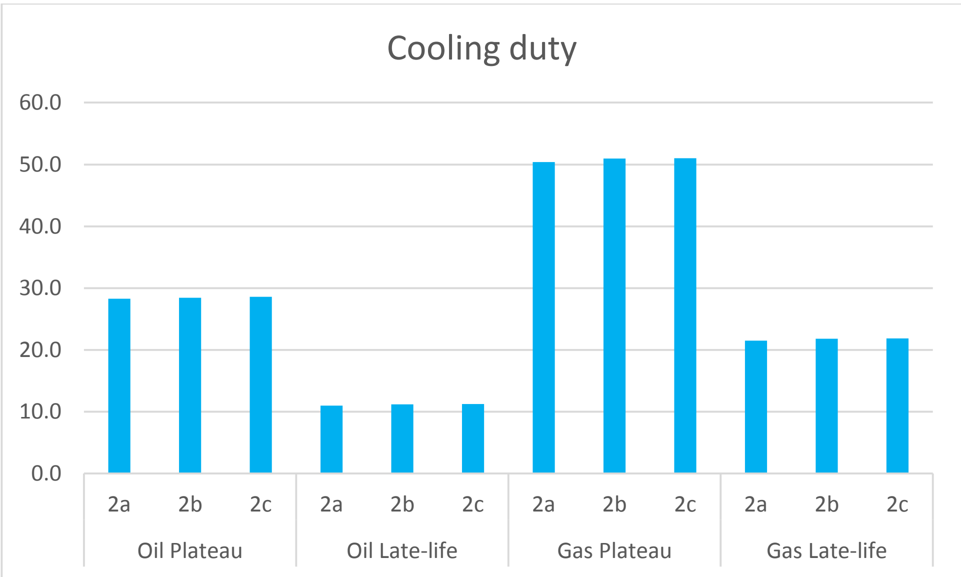

Figure 6-3 Platform cooling duties for the three main power supply alternatives at each operating point.

The cooling duty does not have a direct impact on the energy and exergy efficiencies of the platform. Indirectly however, the cooling increases the power duties due to the need for pumps. The cooling water also contains chemical exergy. The 2b and 2c cases have the highest cooling duties due to the increased flow rate of gas through the final cooler after the HP export compressor.

The platforms in cases 2b and 2c have the same duties independent of whether their power comes from a Norwegian hydro power plant or a German CCGT plant.

6.2 Efficiencies

In this section, the energy and exergy efficiencies calculated for each of the cases in Figure 4-1 are presented. Table 6-1 shows the energy and exergy efficiencies for the oil and gas platform during plateau and late-life production, as well as a lifetime average. Over the platform lifetime, the platform's efficiency is assumed to change linearly from the plateau efficiency to the late-life efficiency. The operational time outside of these two points is not considered. Most focus will be placed on the lifetime efficiencies in the following analysis. As discussed in Section 2.1, it is the efficiency comparisons which are of most interest, rather than the actual efficiencies themselves. To give an indication of the magnitude of the efficiency differences, an increase in the exergy efficiency of the 2a_O_p case by 0.1 %, would lead to a saving of 10 MW of exergy.

Table 6-1 Exergy and energy efficiencies for all platform operating points and cases.

Case	Energy efficiency *(%)*	Energy efficiency (Lifetime avg.) *(%)*	Exergy efficiency *(%)*	Exergy efficiency (Lifetime avg.) *(%)*
2a - Oil plateau	99.43		98.28	
2a - Oil late-life	96.30	97.87	94.29	96.28
2a - Gas plateau	98.84		96.76	
2a - Gas late-life	98.02	98.43	95.78	96.27
2b - Oil plateau	99.49		98.39	
2b - Oil late-life	97.33	98.41	95.45	96.92
2b - Gas plateau	99.63		97.73	
2b - Gas late-life	99.23	99.43	97.11	97.42
2b_O_p + N Hydro	99.38		98.29	
2b_O_ll + N Hydro	97.09	98.23	95.23	96.76
2b_G_p + N Hydro	99.47		97.58	
2b_G_ll + N Hydro	99.00	99.23	96.90	97.24
2b_O_p + German CC	99.31		98.05	
2b_O_ll + German CC	96.93	98.12	94.69	96.37
2b_G_p + German CC	99.36		97.22	
2b_G_ll + German CC	98.85	99.10	96.40	96.81
2c - Oil plateau	99.64		98.57	
2c - Oil late-life	97.50	98.57	95.65	97.11
2c - Gas plateau	99.71		97.81	
2c - Gas late-life	99.33	99.52	97.22	97.52
2c_O_p + N Hydro	99.42		98.36	
2c_O_ll + N Hydro	97.13	98.27	95.31	96.83
2c_G_p + N Hydro	99.49		97.61	
2c_G_ll + N Hydro	99.02	99.25	96.94	97.28
2c_O_p + German CC	99.28		97.89	
2c_O_ll + German CC	96.90	98.09	94.51	96.20
2c_G_p + German CC	99.34		97.14	
2c_G_ll + German CC	98.82	99.08	96.29	96.71

6.2.1 Energy efficiency

The efficiencies given in Table 6-1 are concentrated within a range of 94 – 100 %, making comparison difficult without graphical aids. Figure 6-4 shows the lifetime energy efficiencies for both the oil platform cases and the gas platform cases.

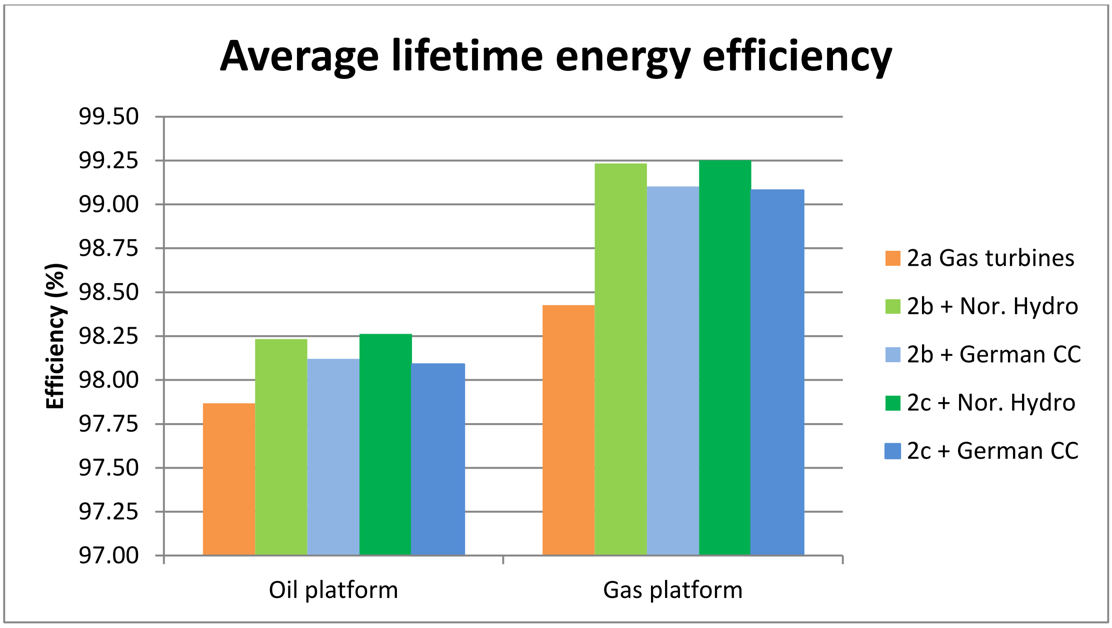

Figure 6-4 Average lifetime energy efficiencies for an oil and a gas platform with different power supply options

The first obvious point of interest is that the gas platform cases have higher energy efficiencies than their oil counterparts. In most of the cases, the equivalent oil and gas platform cases have relatively similar plateau efficiencies. The late-life oil platform efficiency however, is relatively low, reducing the oil platforms lifetime efficiency. This is primarily due to the high rate of produced water injection during late-life oil platform operation.

In the 2a case for example, the gas platform loses more energy in the exhaust stream than the oil case, due the oil platforms high rate of heat recovery. But, the oil case actually loses considerably more heat energy in its water injection stream than it does in the exhaust stream. While the exhaust stream is much hotter than the injection stream (ca. 400 °C as opposed to ca. 50° C) the molar flow in the produced water injection stream is about eight times that of the exhaust stream. This heat loss is in reality difficult to exploit due to its low temperature. This pattern is seen in all of the cases, independent of the power supply. The exergy analysis reduces the weighting of low temperature streams such as this one in the efficiency calculation.

The comparison of the oil and gas platform energy efficiencies for the 2a (gas turbine) case has the opposite result in this thesis from that calculated in the project thesis [3]. The oil platform's lifetime average is about 0.5 % lower than the project thesis equivalent. The gas platform's lifetime average, however, is about 0.4 % higher than its project thesis equivalent. The platform with highest lifetime energy efficiency is thus the gas platform in this thesis. This unexpected difference is primarily the result of the alternative energy calculation method used in this thesis (described in Equations (3-18) and (3-19). This method of calculation also takes the flow enthalpy into consideration, rather than just the heating value as is the case in the project thesis. The reservoir composition and other minor design basis changes are also factors influencing the change.

For both the oil and the gas platform, cases 2b – Nor. Hydro, and 2c – Nor. Hydro have the highest energy efficiencies. This is due to the higher efficiency of the hydro power plants and the lower transmission losses due to the power plant's location on the Norwegian coast.

It is interesting to see here that the electrified platform cases (2b and 2c) have the highest energy efficiencies. Use of gas turbines involves a loss of heat energy. This is most significant on the gas platform, where the lower heat duty leads to large energy losses in the gas turbine exhaust. This is reflected in the large difference between the 2a case efficiency and the other efficiencies for the gas platform. Both the German CC gas power plant and the Norwegian hydro power plant have energy efficiencies of 85 % (when including German district heating). In addition to this are the transmission losses of 15 % and 8 %, respectively, of the power produced in the power plant. The gas turbines in 2a have lifetime efficiency averages of about 38 % and 35 % for the oil and gas platforms respectively. In spite of these transmission losses, the high energy efficiencies of the land-based power plants result in the higher energy efficiencies for the electrified cases. The difference is less pronounced on the oil platform due to the high rate of heat recovery from the gas turbine exhaust in the 2a plateau case.

A pattern can be seen here, where the 2b + Nor. Hydro cases have lower efficiencies than their 2c equivalents. On the other hand, the 2b + Ger. CC cases have higher efficiencies than their 2c equivalents. This would indicate that heat generation with the gas-fired heaters is less efficient than using Norwegian hydro power (and the associated transmission) but more efficient than using a German CCGT plant (and the association transmission).

6.2.2 Exergy efficiencies

Figure 6-5 shows the exergy efficiencies for both the oil platform cases and the gas platform cases, over their lifetimes.

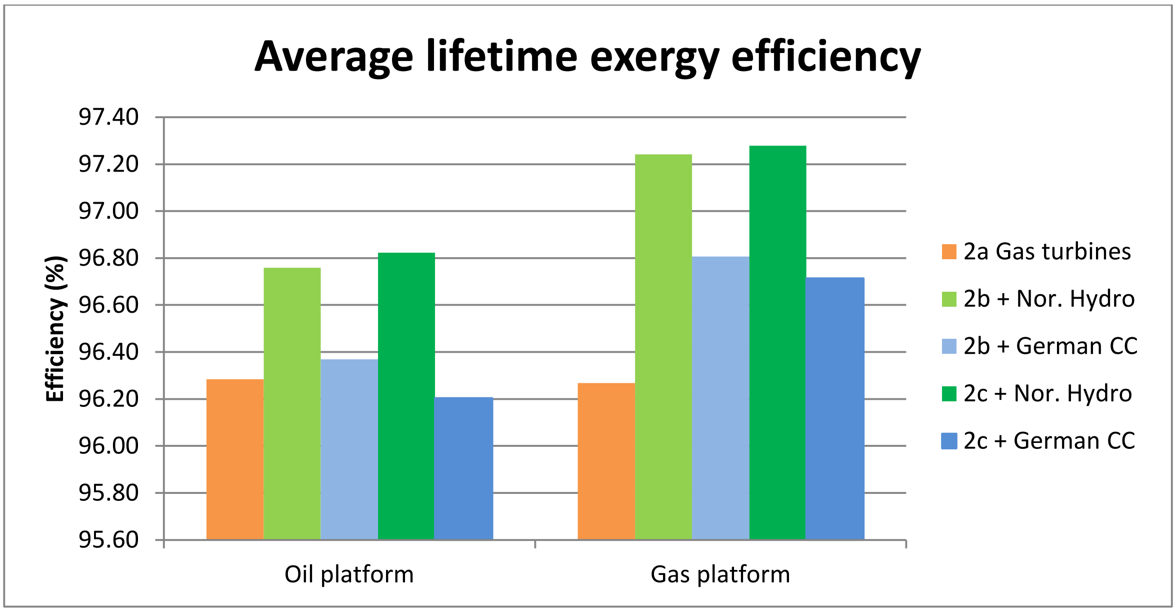

Figure 6-5 Average lifetime exergy efficiencies for an oil and a gas platform with different power supply options

Some similarities can be seen between the lifetime exergy efficiencies in Figure 6-5, and the lifetime energy efficiencies in Figure 6-4. As with the energy efficiency, the gas platform's exergy efficiencies are on average higher for the different power supply alternatives as opposed to their oil platform equivalents. There are however a number differences due to way an exergy analysis measures energy quality. The impact that the inclusion of chemical exergy has had is also visible in these results.

Perhaps the most interesting result from the exergy analysis is that for the oil platform, electrifying the platform, the 2c + Ger. CC case, is less efficient than the 2a case. In the 2c + Ger. CC case, a German power plant must produce enough power to power the platform, as well supply the platform heating duty. In addition to this, enough power must be generated in order to offset the transmission losses. In the oil plateau case this leads to a doubling of the inlet exergy flow required by the German plant in comparison to the actual heat and power duties required by the platform. Offshore gas turbines in the 2a case on the other hand need only cover the power duty, whilst the platform heat duty is provided as a 'bonus' by the gas turbine exhaust.

It is primarily the fact that the platform's heat duty must be produced in a power plant, and then transported, which leads to the 2c + Ger. CC case exergy efficiency being lower than the 2a case on the oil platform. To avoid this, the partial electrification and German power option (2b + Ger. CC), with its marginally higher efficiency (compared to the gas turbine option), is perhaps a more viable in the event an oil platform is to be electrified.

The oil reservoir's composition has been chosen with the intention that it be a 'typical' oil reservoir - neither heavy nor light oil. For other reservoir compositions where, for example the oil is 'lighter', the platform's heat duty will not be as high, increasing the exergy efficiency of the German power plant electrification option. The reverse is of course also true of a heavy oil reservoir – more heat is required to process it. If world oil prices continue to rise, as they have done over the past 50 years, it is likely that more heavy oil reservoirs will be developed and electrification should not automatically be assumed to be the most efficient power supply option for oil platforms. The temperature of the reservoir is another significant factor affecting the platforms heat duty.

It is also clear from Figure 6-5 that the lifetime exergy efficiencies of the hydro power electrification cases (2b + Nor. hydro and 2c+ Nor. hydro) are significantly higher than all other cases, both for the oil platform and the gas platform. This electrification option combines effective power production with relatively low power transmission losses, making it a clear winner.

While the energy efficiencies of the Norwegian hydro power cases (2b + Nor. hydro and 2c+ Nor. hydro) and the German CC gas power cases (2b + Ger. CC and 2c+ Ger. CC) were relatively similar, the exergy efficiencies of the German power option is considerably lower than the Norwegian option. This is primarily due to the lower exergy value placed on low grade heat. The German CCGT cases' district heating product has a much lower exergy value than energy value as the heat transfer occurs at a temperature of 150 °C. In fact its exergy value is less than a third of its energy value.

As mentioned initially, the gas platform's lifetime exergy efficiencies are on average higher than those of the oil platform. It is however difficult to interpret too much from this result. The oil platform's wellstream contains a lot of water, especially late-life, and the platform injects large quantities of water – both reservoir water and seawater. This power demanding injection, and the loss of heat exergy in the water is a factor that reduces the oil platforms overall efficiency. The disadvantages associated with the water injection are however exaggerated by the exergy analysis due to the inclusion of chemical exergy. Water has a relatively low chemical exergy value, but it becomes significant when large quantities of water are involved. In the extreme case, with the highest water injection rate – late-life oil platform production – 88 MW of chemical exergy are 'lost' due to water injection (produced water and seawater). A further 14 MW of chemical exergy are lost in the cooling seawater released into the sea. In comparison, 11 MW of thermomechanical exergy are lost in the injection process and 0.1 MW in the cooling water. This loss of chemical exergy in the water stream is irrelevant, but it has a large effect on the oil platforms exergy efficiency. Rough estimates suggest that removing the chemical exergy of the water from the exergy efficiency calculations would increase all of the oil platform cases' exergy efficiencies by just under 2 %.

It is important to specify that when discussing chemical exergy in the above paragraph, it is the so-called 'component chemical exergy' (the first term in Equation (3-9)) which is being discussed. The exergy of mixing on the other hand is a relevant measure of exergy (although relatively small in this analysis). When performing the energy analysis, the problem does not exist as the heating value (chemical exergy's energy equivalent) has a value of 0 for water.

Whilst it is difficult to compare the exergy efficiencies of the oil platform with those of the gas platform due to the chemical exergy of water, it is possible to make an electrification recommendation. The oil platform electrification options (2b and 2c) increase the platform exergy efficiency by on average 0.26 percentage points (compared to 2a). For the gas platform, electrification (2b or 2c) increases the efficiency by 0.75 percentage points on average. This equates to a gas platform and oil platform saving of about 16 MW and 46 MW of exergy respectively, when electrifying. This result would suggest that from an exergy efficiency point of view, gas platform electrification (partial or full) will give the highest returns.

6.3 CO_2 emissions

CO_2 emission data has also been calculated for each of the case. Table 6-2 and Figure 6-6 show the lifetime average CO_2 emissions calculated for these cases. Appendix F shows CO_2 emission data for both plateau and late-life production.

Table 6-2 Average yearly CO2 emission for the oil and gas platforms with different power supply option

Average lifetime CO2 emissions (Tonne/year)

	Oil platform	Gas platform
2a Gas turbines	142719	193505
2b + Nor. Hydro	17856	9006
2b + German CC	123011	141477
2c + Nor. Hydro	0	0
2c + German CC	184089	172556

While these figures are primarily for comparing the different cases looked at in this thesis, it is interesting to compare the figures with an operational platform. The Kristin platform is a relatively new (2005 production start [29]) gas turbine-powered platform in the Norwegian Sea, with a total (electrical and mechanical) power duty of about 50 MW. In 2012, the platform emitted 216197 tonnes of CO_2 [30]. This thesis' gas turbine-powered gas platform at plateau production has a power duty of just over 50 MW and a CO_2 emission rate of 261966 tonnes per year. This result would suggest that the CO_2 calculation method used in this thesis is sound.

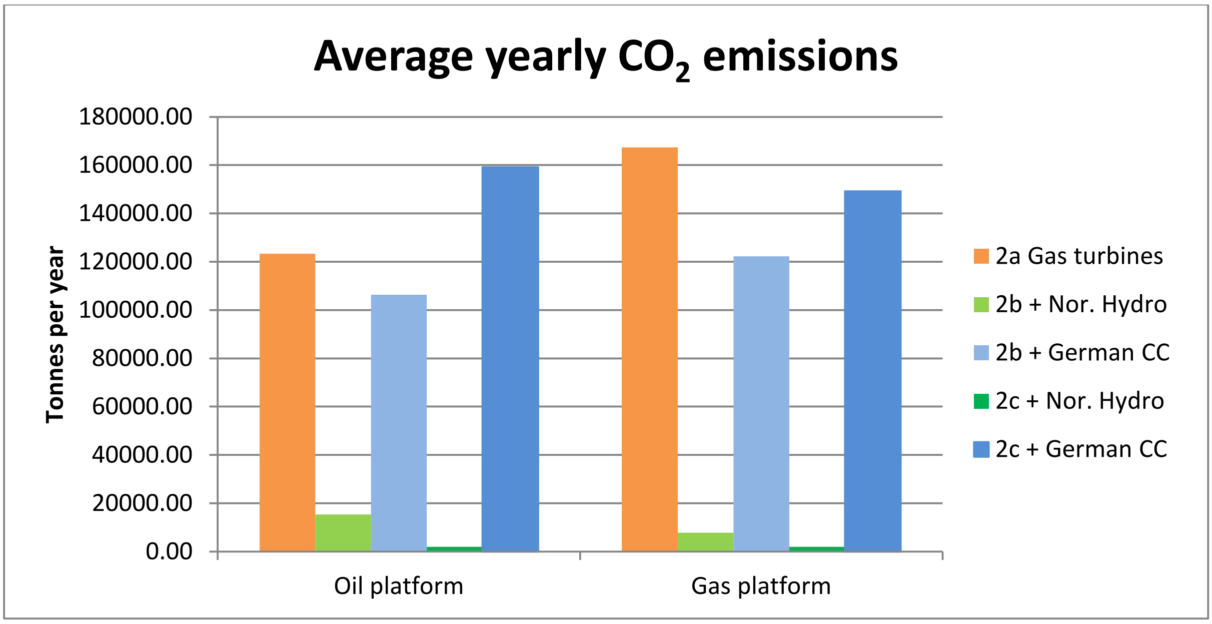

Figure 6-6 Average yearly CO_2 emission for the oil and gas platforms with different power supply options

It is clear from Figure 6-6 that the Norwegian hydro power cases have the lowest CO_2 emission of the cases, with very little emissions from the 2b cases and no emissions from the 2c cases. It is the 2a, and German CCGT cases which are however most interesting. On the oil platform, it is the 2c + Ger. CC case which leads to the highest CO_2 emissions over the platform's lifetime. This is the result of the relatively large amounts of fuel gas required by the German power option to cover the platform's heat and power duties, as well as overcome transmission and heater losses. The 2b + Ger. CC case on the oil platform does however have lower CO_2 emission rate. The 2b + Ger. CC option has a lower emission rate than the 2c + Ger. CC option as it does not need to produce and transport the heat duty as power, but rather this is produced offshore in the relatively efficient gas-fired heaters.

For the gas platform, it is the 2a case which has the greatest CO_2 emission rate. The 2b + Ger. CC case has once again a lower emission rate than 2c + Ger. CC, for the same reasons mentioned above. The gas turbine case has higher emissions on the gas platform than on the oil as a direct consequence of the platform's higher power duty. The 2b and 2c cases with German CCGT power, are both lower than the 2a case on the gas platform due to the relatively low heat duty. A lower heat duty means that less power needs to be generated and transported in the 2c case, and the benefits of the offshore heat production in the 2b case are reduced.

The CO_2 emission results suggest that it would be most beneficial to electrify a gas platform for CO_2 emission reduction. The gas platform cases have higher emission rates than each of their equivalent oil platform cases and all of the electrification options emit less CO_2 than the gas turbine-powered case. This supports the findings of the exergy analysis regarding the choice of platform for electrification. The results also make it clear that electrification of a platform does not necessarily lead to CO_2 emission reduction; it depends on the source of the electricity and the platform's heat duty.

6.4 Sensitivity

A simple sensitivity test has been performed for some of the cases in order to get an idea of the efficiencies' sensitivity to some of the factors. The ranges for which the variables have been tested are assumed to represent realistic variations in the factors looked at.

For case 2b_G_ll + Nor. Hydro, the power transmission losses (8 %) were adjusted down to the minimum (6 %) and up to the maximum (10 %) loss percentages as given in Table 3-1. This two percentage point adjustment up or down changed the overall case energy and exergy efficiencies by on average -0.022 % or 0.021 % respectively. Similar results were seen for the other Norwegian Hydro power plant cases.

The energy and exergy efficiency responses to changes in the gas turbine part load operation point (and thus efficiency) were also tested. The gas turbines in the simulations are operating at loads of between about 74 and 100 %. To test the efficiency sensitivities to this factor, the gas turbine efficiencies were adjusted by artificially increasing or decreasing the gas turbine loads by 20 percentage points. The changes in the energy and exergy efficiencies for the systems were then calculated. The average change in the exergy efficiency per 10% change in the turbine load was 0.118 percentage points. For the energy efficiency, this was calculated to be 0.129 percentage points. See Appendix Q for a table of results for this analysis.

The gas turbine's efficiency variation, which follows from its load variation, appears to have a greater impact on the overall case efficiencies than the expected variation in the power transmission losses. This is assumed to be the case for the German and Norwegian power plant efficiencies also.

Another factor which is expected to have a relatively large impact on the energy and exergy efficiencies is the reservoir composition. The heat required to stabilise the oil is directly related to the oil composition and this heat duty has a large impact on the system's energy and exergy efficiencies.

6.5 Result comparison

It can be seen from the literature review that the majority of the platform exergy analyses found, focused on the subsystems of the platform. In the cases where Tuong-Van and Voldsund gave overall exergy efficiencies, the power generation systems were not included in the control volume. Chemical exergy could then be excluded from their efficiency calculations and efficiencies in the order of 30 % - 50 % were calculated. This type of efficiency calculation was not possible in this thesis, making a result comparison meaningless. Rian's [10] analysis does however give results for the complete platform in which a similar efficiency calculation method has been used.

Rian calculates an energy efficiency of 93.3 % and an exergy efficiency of 95 %. The efficiencies are slightly lower than those found in this thesis. An LNG liquefaction plant is more complex than an offshore processing plant and one would thus expect it to require more energy/exergy to operate, leading to lower efficiencies. In addition, the Rian's energy efficiency is lower than the exergy efficiency due to the low amount of energy in the cold LNG product.

6.6 Exergy analysis consideration

The experience of using of an exergy analysis has confirmed some of the advantages inherent to the method, as well as uncovered some of the challenges associated with it.

One of the clear strengths of the method is the qualification of energy quality. Low temperature, low quality heat flows have much less influence on the overall efficiencies when considered in an exergy analysis rather than an energy analysis. For example, the energy associated with low temperature water in the inlet, which is then 'lost' to reinjection does not have as negative an effect on the exergy efficiency as it does the energy efficiency. And rightly so, this is energy which has little value in reality.

The flipside is the component chemical exergy associated with for example water. The chemical exergy of water is worthless to the platform, but the large volumes flowing into the system, before being 'lost', leads to an artificial efficiency reduction.

It is not just the chemical exergy related to relatively worthless substances like water that lead to challenges. The chemical exergies of the hydrocarbons are large values which dwarf the thermomechanical exergies in most of the streams on the platform. But It is the thermomechanical exergy losses and destruction which may be able to be reduced, and thus the most interesting fraction of the stream's exergy.

For a processing facility such as an oil or gas platform, which operates primarily as a separator, the chemical exergy leaving the control volume as a product is not much less than that of the inlet stream. This leads to high efficiencies. It is difficult to argue for the electrification of a platform when it appears to only increase the efficiency by less than a percentage point, when comparing it with a gas turbine powered platform. This is one of the weaknesses with the method of exergy analysis chosen.

The greatest advantage with exergy analysis would appear lie in its ability to compare subsystems of a process, in order to isolate sources of exergy destruction and where efficiency improvement efforts should be concentrated. With some adjustments to the way the exergy analysis was carried out, the method has potential to give even better results (discussed further in Section 8).

7 Conclusion

Exergy analyses have been performed for both an oil and a gas producing offshore platform for different operation points in their lifetimes. The analyses have been carried out for cases where power and heat have been supplied by gas turbines, partial electrification with gas-fired heaters or full electrification. The electrification options have in addition been analysed with different land based power options – German combined cycle gas power and Norwegian hydro power.

A literature study has revealed a number of exergy analyses focusing on the different subsystems of an offshore platform. An exergy analysis of a complete land based LNG plant has also been studied. The knowledge gained from these papers has helped form the exergy analysis conducted in this thesis.

The results of this analysis show that platform electrification does, in many scenarios, lead to emission reduction and efficiency increases. This is primarily due to the higher efficiencies of the land based power generation. There are however some cases where the opposite appears to be true. Full electrification of an oil platform with power from a German CCGT plant, can lead to lower system efficiencies and higher CO_2 emissions than if gas turbines had been used. In this situation, the entire heat and power duty must be produced as electricity, then transmitted to the platform. The losses associated with power generation and transmission are thus applied to both the power and the heat duties leading to the lower overall efficiency and higher CO_2 emissions.

This is an analysis which is very case dependent and should as such be performed anew for any proposed electrification project. Some of the factors which would appear to be most important to the analysis are the oil composition and conditions in the reservoir, platform distance from land and the degree of part load gas turbine operation. The major variable in this thesis – the electricity source – is a relatively difficult factor to define and isolate due to the open European power market.

8 Future work

A great deal has been learned from the work undertaken as part of this thesis. The topic of platform electrification is very interesting and there a number of topics which could have been pursued further. Some aspects of this paper could also have been conducted differently.

A natural improvement would be to calculate the exergy efficiencies in such a way that the impact of the large hydrocarbon chemical exergies was removed. This would lead to more meaningful and useful results. Tuong-Van and Voldsund have achieved this for the smaller process sub-systems they have studied, and Rian has suggested a method in her most recently publicised Snøhvit article [10] which may work well for this thesis' system.

As mentioned previously, excluding the chemical exergy of water may also lead to more realistic results. By setting water's chemical exergy to zero, this portion of the total chemical exergy would be removed from the inlet stream and the different 'loss' streams. This would allow a truer comparison of the oil and gas platform exergy efficiencies.

Due to time restraints, the electrical transmission loss assumptions are relatively simple. The losses are constant, independent of the amount of power required by the platform. It would have been interesting to calculate actual power loss in each of the cases, based on the amount of power being transmitted.

A couple of improvements could also have been made to the hydro power plant. For the sake of consistency, the water exergy could also have been included in the calculation here, since this was the case for the water flow through the platform. Alternatively it could continue to be neglected if the suggestion in the above paragraph is employed. The hydro power plant could have been given a higher efficiency (90 % +) in order to reflect some of the larger and newer plants, if it is indeed to be the 'best case scenario' when comparing the electrification options. This would however not have affected the outcome of the comparison in this thesis.

In addition, there are some of other topics which could be looked further into. More accurate efficiencies for gas-fired heaters could have been used, in order to get more accurate results in the 2b cases. A lower environmental temperature could have been used, better reflecting the true average temperature in the North Sea. An old coal power plant could have been considered as the German power option, perhaps better representing the 'worst case scenario' of 'high emission, low efficiency power imported from Europe'. Europe imports a significant portion of its gas from Norway. The losses involved with piping the gas from Norway to Europe could thus also have been included in the exergy analysis.

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Appendix A

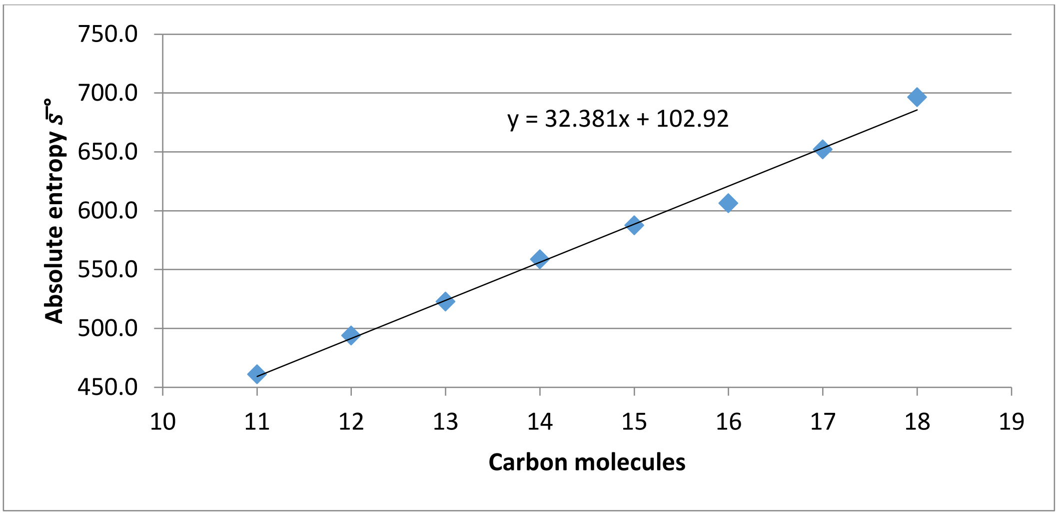
The single phase assumption for the calculation of chemical exergies (mentioned in Section 3.1.4) was tested to see what effect it would have on the total exergy of a stream. The wellstream in the gas plateau case was tested. First, the gas-to-liquid ratio was determined for each component 'i' in the flow as in the equation below.

$$(\text{Gas to liquid ratio})_{\text{i}} = \frac{(gas\ phase\ molar\ flow\ rate)_i}{(liquid\ phase\ molar\ flow\ rate)_i}$$

Components with a ratio less than 0.1 were considered to be liquid, and those with a ratio over 0.9 were considered to be gases. For the remaining 'two-phase' components (C8 – C11 in this test), standard chemical exergies were calculated as described in Section 3.1.4 (for their gaseous phases) or found in tables (for their liquid phases). The total exergy of the wellstream (including thermomechanical exergy) was determined for the case where the 'two-phases components' were considered liquids and the case where the 'two-phase' components were considered gases. The difference in exergy flows of the streams was calculated to be 0.005% (9666.003 MW vs 9666.52 MW). A negligible difference. It is assumed that this effect of the single phase assumption, will be of a similar order of magnitude in the other platform cases.

Appendix B

When calculating the standard chemical exergy of a hydrocarbon, the absolute entropy of the hydrocarbon is needed. This information was not available for the hydrocarbon chains C19 and C20 in the liquid phase, requiring an extrapolation of the liquid phase absolute entropies of C11 to C18. The absolute entropy of the C11 – C18 increased linearly in relation to the increasing number of hydrocarbon carbon molecules as shown in the figure below. This trend was assumed to continue for C18 and C19.



Appendix C

Reference library for the calculation of standard chemical exergies of hydrocarbons.

Library:			reference
$\bar{e}^{ch}_{CO_2}$	20170	kJ/kmol	Kotas
$\bar{e}^{ch}_{H_2O\,(l)}$	3120	kJ/kmol	Kotas
$\bar{e}^{ch}_{O_2}$	3970	kJ/kmol	Kotas
$\bar{s}_{CO_2}$	213.69	kJ/(kmol*K)	M&S
$\bar{s}_{H_2O\,(l)}$	69.95	kJ/(kmol*K)	M&S
$\bar{s}_{O_2}$	205.03	kJ/(kmol*K)	M&S
$\bar{h}°_{CO_2}$	-393520	kJ/kmol	M&S
$\bar{h}°_{H_2O}$	-285830	kJ/kmol	M&S
$\bar{h}°_{O_2}$	0	kJ/kmol	M&S
T_0	298.15	K	
where:			
$\Delta_F H°$	=	Enthalpy of formation	
$\Delta_C H°$	=	Enthalpy of combustion	
$\Delta S°$	=	Entropy change	
$\bar{e}^{ch}$	=	Specific chemical exergy	
$\bar{s}$	=	Absolute entropy	
$\bar{h}$	=	Enthalpy of formation	

The chemical exergy calculation worksheet on the next page was created in order to calculate the standard chemical exergies of those hydrocarbons not included in Kotas' tables. The chemical exergies of a number of the components that are included in Kotas' table are also calculated in order to check the calculation method used.

The chemical exergies have been calculated (using Equations (3-10),(3-11) and (3-12)) for both the gas and the liquid form of each component, when possible, in order to check the magnitude of the phase change exergy and evaluate whether this is necessary to include.

Chemical exergy calculation worksheet.

								Data fra nist.gov --->								
								S°	$\Delta_F H°$	$\Delta_C H°$	$\Delta_F H°$	$\Delta_C H°$	HHV	ΔS°		$\bar{e}^{ch}$
	phase							kJ/(kmol*K)	kJ/mol	kJ/mol	kJ/kmol	kJ/kmol	kJ/kmol	kJ/(kmol*K)		kJ/kmol
Hydrocarbon fuel		(C	H)	+ O_2 →	CO_2 +	$H_2O_{(l)}$										
Methane	g	1	4	2	1	2		186.3		-890.8	0.0	-890752.5	890752.5	242.7		836852.6
Propane	l	3	8	5	3	4		171.0	-119.8		-119800.0	0.0	2204080.0	275.3		2175145.3
Pentane	l	5	12	8	5	6		261.8		-3509.2	0.0	-3509230.0	3509230.0	413.9		3473626.8
Octane	g	8	18	12.5	8	9		467.1	-208.6		-208550.0	0.0	5512080.0	690.9		5445913.6
Nonane	g	9	20	14	9	10		506.5	-228.3		-228300.0	0.0	6171680.0	754.2		6103962.3
Decane	g	10	22	15.5	10	11		545.8	-249.7		-249700.0	0.0	6829630.0	817.4		6760402.7
Undecane	g	11	24	17	11	12		583.6	-270.3		-270300.0	0.0	7488380.0	879.1		7418096.3
	l	11	24	17	11	12		461.1		-7428.9	0.0	-7428850.0	7428850.0	756.6		7395091.2
Dodecane	g	12	26	18.5	12	13		622.5	-289.5		-289500.0	0.0	8148530.0	941.9		8076850.1
	l	12	26	18.5	12	13		493.9		-8086.5	0.0	-8086500.0	8086500.0	813.3		8053168.1
Tridecane	g															
	l	13	28	20	13	14		522.9		-8739.7	0.0	-8739700.0	8739700.0	866.2		8707932.5
Tetradecane	l	14	30	21.5	14	15		558.9			0.0	0.0	0.0	926.1		-32291.7
Pentadecane	l	15	32	23	15	16		587.5		-10047.3	0.0	-10047300.0	10047300.0	978.7		10016672.5
Hexadecane	g	16	34	24.5	16	17		778.3	-374.8		-374800.0	0.0	10780630.0	1193.4		10703326.2
	l	16	34	24.5	16	17		606.5		-10699.1	0.0	-10699100.0	10699100.0	1021.5		10673024.3
Heptadecane	l	17	36	26	17	18		652.2		-11351.2	0.0	-11351200.0	11351200.0	1091.2		11321691.7
Octadecane	l	18	38	27.5	18	19		696.6		-12008.7	0.0	-12008700.0	12008700.0	1159.5		11976173.5
Nonadecane	l	19	40	29	19	20		718.2		-12662.6	0.0	-12662600.0	12662600.0	1204.9		12633853.4
Eicosane	l	20	42	30.5	20	21		750.5		-13316.4	0.0	-13316400.0	13316400.0	1261.2		13288206.7

Appendix D

Calculation of the kinetic and potential exergy of the oil export pipeline flow on the oil platform.

Kinetic exergy negligible	
Appropriate pipe dimensions and flow velocity for oil platform oil export pipe calculated using internal Aker Solutions calculations software:	
Diameter: 10", giving V = 6m/s	
E^k = (V^2)/2 = 18.22 J/kg	
= 3679 J/kmol	For M = 201.9 kg/kmol
=3.7 kJ/kmol	
= negligible	
m2/s2 = (kg.(m/s2).m) /kg = (Nm) /kg=J/kg	

Potential exergy negligible		
E^P = gz	= 9.82 m/s2 x 30m	
	= 294.6 J/kg	
	= 59479 J/kmol	For M = 201.9 kg/kmol
	= 59.5 kj/kmol	
	= negligible	

Appendix E

Mass, energy and thermal energy balances for each of the cases, calculated by subtracting the outlet streams from the inlet streams. It can be seen that the mass and energy balances are very close to zero. The in-out difference is negligible. The thermal energy balances do however have a small differential due to the way the thermal energy is calculated. The ramifications of this are mentioned in Section 5.4. The mass and energy balances are the same, independent of the electricity's source which is why the 'Nor. Hydro' and 'German CC' balances have been left blank.

	Mass balance		Energy balance		"Thermal Energy balance"	
	kg/h	% Inlet	MW	% Inlet	MW	% Inlet
2a - Oil plateau	0.78	3E-05	0.00360	-5E-05	-8.07	-0.093
2a - Oil late-life	-0.15	-7E-06	0.00302	-3E-05	-5.71	-0.194
2a - Gas plateau	1.94	1E-04	-0.00003	2E-07	-12.56	-0.145
2a - Gas late-life	-0.06	-2E-05	-0.00008	1E-06	-7.46	-0.258
2b - Oil plateau	0.10	4E-06	0.00360	-5E-05	-6.61	-0.076
2b - Oil late-life	-0.15	-6E-06	0.00302	-3E-05	-2.40	-0.081
2b - Gas plateau	0.21	3E-05	-0.00003	2E-07	-10.25	-0.118
2b - Gas late-life	-0.06	-2E-05	-0.00008	1E-06	-3.65	-0.125
2b_O_p + N Hydro					-6.61	-0.076
2b_O_ll + N Hydro					-2.40	-0.080
2b_G_p + N Hydro					-10.25	-0.117
2b_G_ll + N Hydro					-3.65	-0.125
2b_O_p + German CC					-6.61	-0.075
2b_O_ll + German CC					-2.40	-0.080
2b_G_p + German CC					-10.25	-0.117
2b_G_ll + German CC					-3.65	-0.124
2c - Oil plateau	0.70	3E-05	0.00364	-5E-05	-2.60	-0.030
2c - Oil late-life	-0.15	-6E-06	0.00302	-3E-05	-0.87	-0.029
2c - Gas plateau	2.71	4E-04	-0.00219	2E-05	-8.15	-0.093
2c - Gas late-life	-0.94	-4E-04	0.00023	-4E-06	-2.69	-0.092
2c_O_p + N Hydro					-2.68	-0.031
2c_O_ll + N Hydro					-0.90	-0.030
2c_G_p + N Hydro					-8.18	-0.094
2c_G_ll + N Hydro					-2.71	-0.093
2c_O_p + German CC					-2.68	-0.030
2c_O_ll + German CC					-0.90	-0.030
2c_G_p + German CC					-8.18	-0.093
2c_G_ll + German CC					-2.71	-0.092

Appendix F

CO_2 emission data for all platform cases. An average of 347 production days per year is assumed when calculating yearly production rates.

Platform CO_2 Emissions			
	Tonne/day	Tonne/year	Average lifetime CO2 emissions/year
2a - Oil plateau	433	129787	
2a - Oil late-life	390	116989	123388
2a - Gas plateau	755	226483	
2a - Gas late-life	360	108107	167295
2b - Oil plateau	71	21230	
2b - Oil late-life	32	9645	15437
2b - Gas plateau	34	10190	
2b - Gas late-life	18	5383	7786
2b_O_p + N Hydro	71	21230	
2b_O_ll + N Hydro	32	9645	15437
2b_G_p + N Hydro	34	10190	
2b_G_ll + N Hydro	18	5383	7786
2b_O_p + German CC	404	121269	
2b_O_ll + German CC	305	91431	106350
2b_G_p + German CC	554	166060	
2b_G_ll + German CC	262	78568	122314
2c - Oil plateau	0	0	
2c - Oil late-life	0	0	0
2c - Gas plateau	0	0	
2c - Gas late-life	0	0	0
2c_O_p + N Hydro	0	0	
2c_O_ll + N Hydro	0	0	0
2c_G_p + N Hydro	0	0	
2c_G_ll + N Hydro	0	0	0
2c_O_p + German CC	660	197894	
2c_O_ll + German CC	401	120416	159155
2c_G_p + German CC	676	202729	
2c_G_ll + German CC	319	95639	149184

Appendix G

Exergy lost and exergy destroyed in all of the cases, both as an absolute value in MW, and as a percentage of the exergy entering the control volume.

	Exergy lost		Exergy destroyed	
	MW	% of Inlet energy	MW	% of Inlet exergy
2a - Oil plateau	92	0.98	52.28	0.56
2a - Oil late-life	130	4.07	37.27	1.17
2a - Gas plateau	169	1.81	118.07	1.26
2a - Gas late-life	76	2.44	41.12	1.31
2b - Oil plateau	96	1.02	38.71	0.41
2b - Oil late-life	118	3.67	13.33	0.41
2b - Gas plateau	143	1.52	54.41	0.58
2b - Gas late-life	61	1.94	15.03	0.48
2b_O_p + N Hydro	96	1.02	47.89	0.51
2b_O_ll + N Hydro	118	3.66	20.84	0.65
2b_G_p + N Hydro	143	1.52	68.71	0.73
2b_G_ll + N Hydro	61	1.94	21.74	0.69
2b_O_p + German CC	101	1.08	65.18	0.69
2b_O_ll + German CC	123	3.78	34.98	1.08
2b_G_p + German CC	152	1.60	95.64	1.01
2b_G_ll + German CC	65	2.05	34.39	1.08
2c - Oil plateau	83	0.89	34.82	0.37
2c - Oil late-life	114	3.52	11.86	0.37
2c - Gas plateau	137	1.46	52.60	0.56
2c - Gas late-life	59	1.86	14.19	0.45
2c_O_p + N Hydro	83	0.89	56.40	0.60
2c_O_ll + N Hydro	114	3.50	23.53	0.73
2c_G_p + N Hydro	137	1.45	71.96	0.76
2c_G_ll + N Hydro	59	1.85	23.32	0.73
2c_O_p + German CC	94	1.00	88.75	0.94
2c_O_ll + German CC	120	3.67	44.34	1.35
2c_G_p + German CC	149	1.56	106.99	1.12
2c_G_ll + German CC	64	2.00	39.85	1.24

Appendix H

Design basis for the four platform cases.

Project Design Basis

Specification		Unit	Typical oil field		Typical gas field	
			Plateau	Late-Life	Plateau	Late-Life
Volume	flow rate (After processing)	Barrels/day	130000	43333	-	-
Volume	flow rate (Before processing)		-	-	LHV flow equal to oil counterpart	
Inlet valve	Pressure	bara	20	20	200	120
	Temperature	°C	50	50	60	60
1st stage Separator	Pressure	bara	16	16	70	70
Gas export:	Pressure	bara	180	180	180	180
	Temperature	°C	60	60	60	60
	Max Cricondenbar	bara	105	105	105	105
	Water Dew point	°C @70 bara	-20	-20	-20	-20
Oil/condensate Export:	Pressure	bara	105	105	105	105
	True Vapour Pressure	bara @ 37.8°C	≤ 0.95	≤ 0.95	≤ 0.95	≤ 0.95
	Max Water content	Vol %	0.5	0.5	0.5	0.5
Process cooling temperature		°C	30	30	25	25
Sea water temperature		°C	15	15	15	15
Non-Process power requirements		MW	6.5	6.5	6.5	6.5
Non-Process heat requirements		MW	4.5	4.5	4.5	4.5
Non-Process cooling requirements (HVAC)		MW	3	3	3	3
Drilling		MW	5.5	4	5.5	4
Water injection pressure		Bara	150	150	-	-

Appendix J

Reservoir compositions for the four platform cases.

Oil reservoir plateau composition

Component	Mole Fraction	
Nitrogen	0.65%	0.006516416
CO2	0.09%	0.000940666
Methane	19.15%	0.191538166
Ethane	5.62%	0.056176432
Propane	6.32%	0.063199894
i-Butane	1.23%	0.012331632
n-Butane	2.69%	0.026866789
i-Pentane	1.13%	0.011319333
n-Pentane	1.41%	0.014130122
C6	1.96%	0.019616961
C7	3.01%	0.030077670
C8	3.26%	0.032610631
C9	2.36%	0.023603416
C11	6.14%	0.061362038
C14	5.86%	0.058553859
C17	4.42%	0.044158862
C20	16.34%	0.163377605
H2O	18.36%	0.183619508

Oil reservoir late-life composition

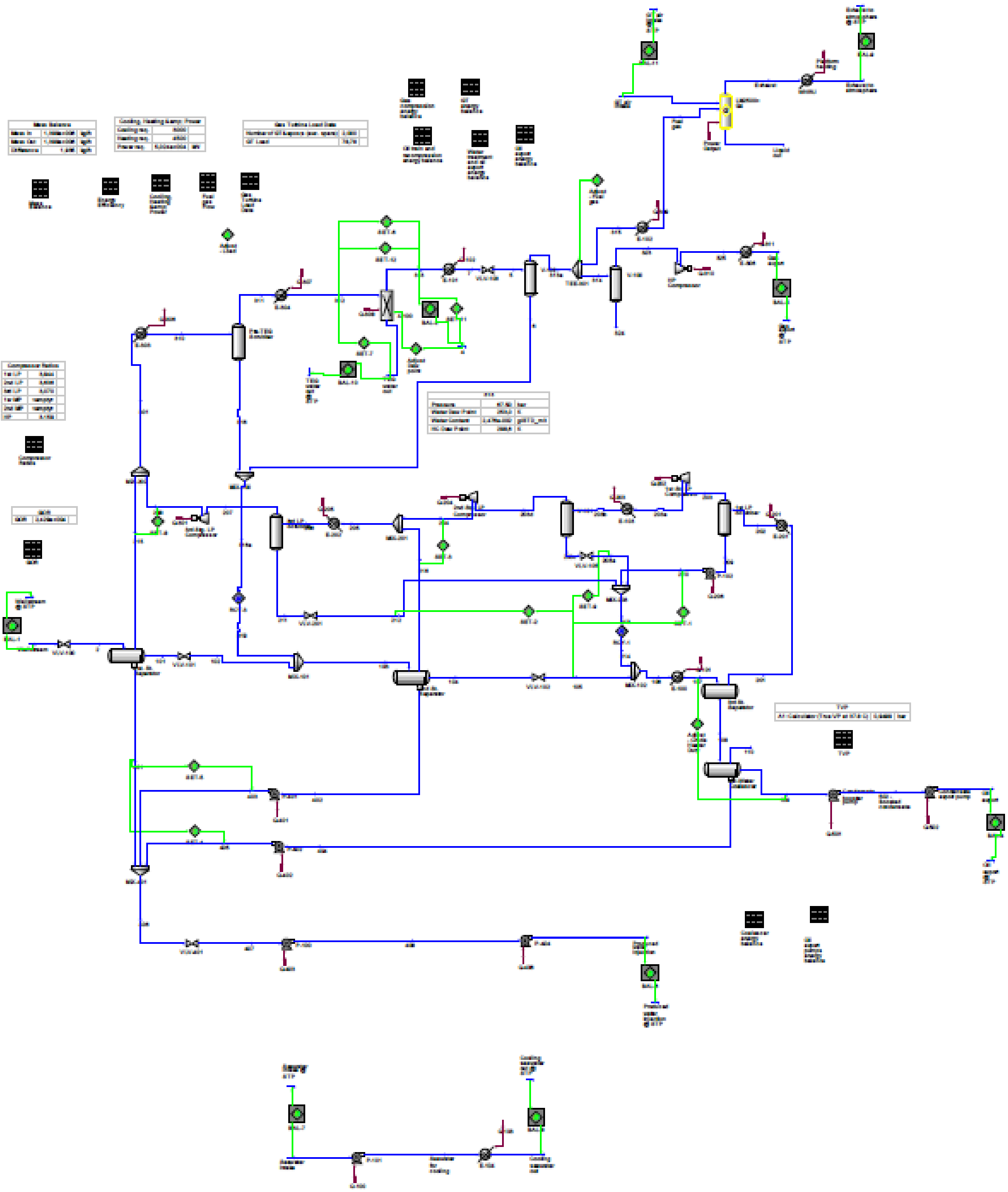
Component	Mole Fraction	
Nitrogen	0.02%	0.000177089
CO2	0.00%	0.000025563
Methane	0.52%	0.005205211
Ethane	0.15%	0.001526642
Propane	0.17%	0.001717510
i-Butane	0.03%	0.000335123
n-Butane	0.07%	0.000730128
i-Pentane	0.03%	0.000307612
n-Pentane	0.04%	0.000383998
C6	0.05%	0.000533107
C7	0.08%	0.000817386
C8	0.09%	0.000886221
C9	0.06%	0.000641443
C11	0.17%	0.001667565
C14	0.16%	0.001591250
C17	0.12%	0.001200054
C20	0.44%	0.004439924
H2O	97.78%	0.977814172

Typical Gas - Plateau & late-life composition

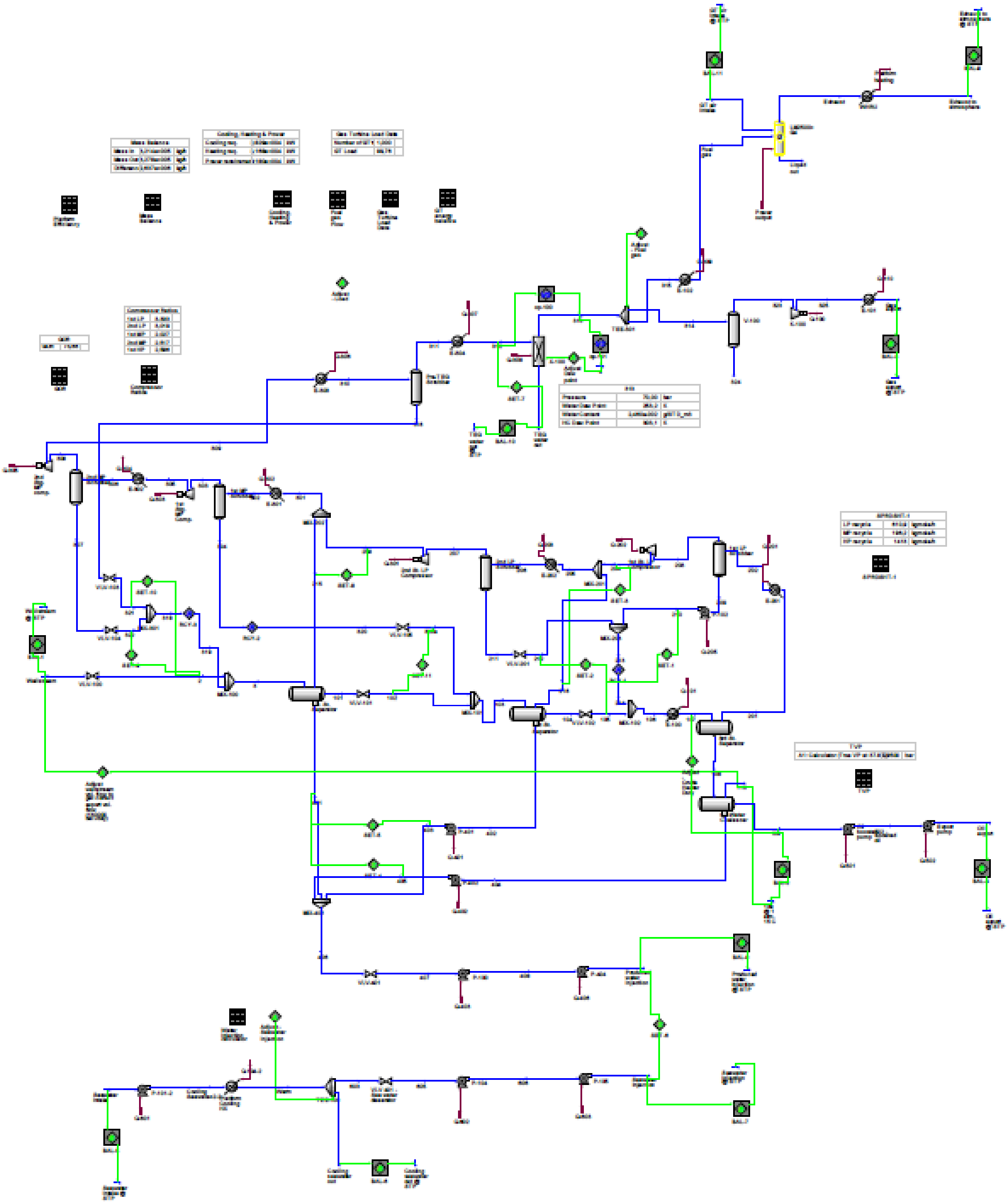
Component	Mole Fraction	
Methane	81.42%	0.8142
Ethane	4.77%	0.0477
Propane	2.42%	0.0242
n-Butane	0.60%	0.006
i-Butane	0.38%	0.0038
n-Pentane	0.23%	0.0023
i-Pentane	0.27%	0.0027
n-hexane	0.32%	0.0032
n-heptane	0.35%	0.0035
n-octane	0.29%	0.0029
H2O	1.04%	0.0104
CO2	4.84%	0.0484
Nitrogen	2.40%	0.024
n - nonane	0.12%	0.0012
Benzene	0.06%	0.0006
Toluene	0.08%	0.0008
M xylene	0.05%	0.0005
N-decane	0.12%	0.0012
N-undecane	0.05%	0.0005
N-dodecane	0.05%	0.0005
N-tridecane	0.04%	0.0004
N-tetradecane	0.03%	0.0003
N-pentadecane	0.02%	0.0002
N-heksadecane	0.01%	0.0001
N-heptadecane	0.01%	0.0001
N-oktadecane	0.01%	0.0001
N-nonadecane	0.01%	0.0001
N-eicosane	0.01%	0.0001

Appendix K

Gas platform HYSYS simulation



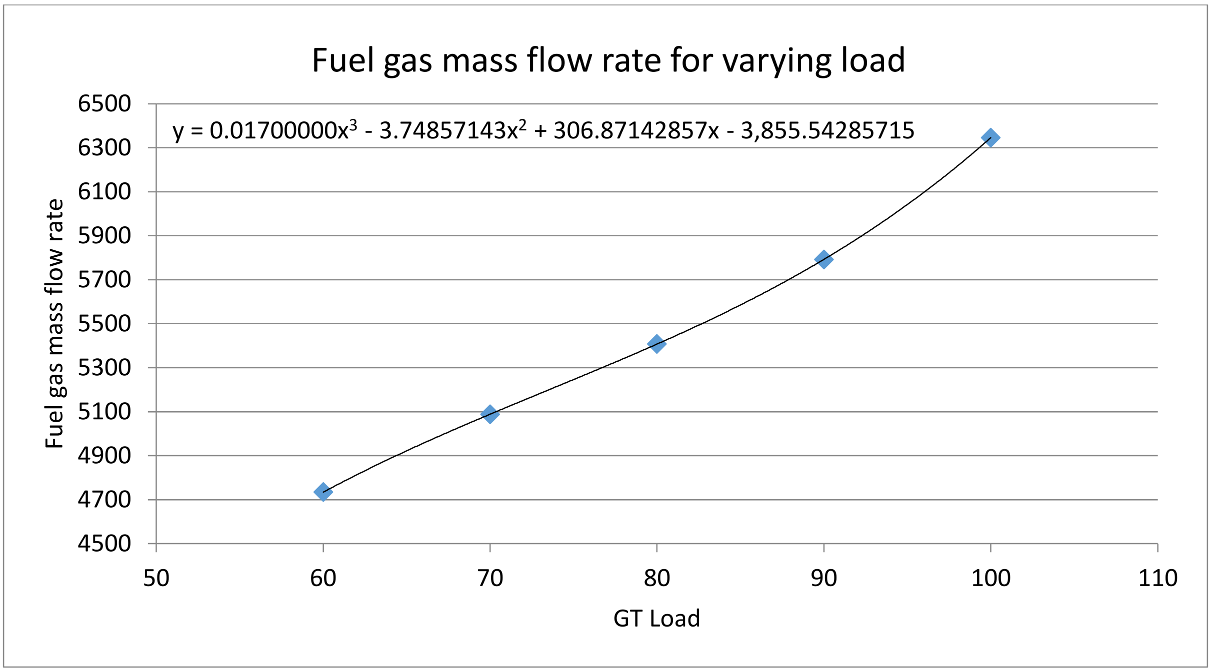
Oil platform HYSYS simulation



Appendix L

Data from GE used to model the gas turbine operation. The fuel gas mass flow rate given here is for a certain gas composition. By using the LHV for this gas (also supplied by GE), together with that of the fuel gas in HYSYS, the required fuel gas flow rate is determined.

GT power loading (%)	60	70	80	90	100
Fuel gas mass flow (kg/h)	4734	5088	5408	5792	6346



Appendix M

The table below is the chemical exergy 'library' used in all of the exergy analyses. The values have a number of sources – primarily Kotas' textbook on the subject of exergy analysis [14]. Some of the values have been calculated using the method described in Section 3.1.4. The unshaded values have been neither calculated nor found in reference material and have thus been assumed to have the same value as for the other phase.

Chemical exergy library				
Component		Chem. Ex (kJ/mol)		Reference
		Gas	Liquid	
n-C20	C20H42	13288207	13288207	Calculated
n-C19	C19H40	12633853	12633853	Calculated
n-C18	C18H38	11981110	11981110	Calculated
n-C17	C17H36	11321692	11321692	Kotas
n-C16	C16H34	10703325	10678810	Kotas, gas phase calculated
n-C15	C15H32	10023870	10023870	Kotas
n-C14	C14H30	9368970	9368970	Kotas
n-C13	C13H28	8714200	8714200	Kotas
n-C12	C12H26	8076850	8059340	Kotas, gas phase calculated
n-C11	C11H24	7418096	7404520	Kotas, gas phase calculated
n-Decane	C10H22	6749750	6749750	Kotas
n-Nonane	C9H20	6093550	6093550	Kotas
n-Octane	C8H18	5440030	5440030	Kotas
n-Heptane	C7H16	4786300	4786300	Kotas
n-Hexane	C6H14	4134590	4130570	Kotas
n-Pentane	C5H12	3477050	3475590	Kotas
i-Pentane	C5H12	3477050	3475590	Kotas
n-Butane	C4H10	2818930	2818930	Kotas
i-Butane	C4H10	2818930	2818930	Kotas
Propane	C3H8	2163190	2175145	Kotas, liquid phase calculated
Ethane	C2H6	1504360	1504360	Kotas
Methane	CH4	836510	836510	Kotas
Toluene	C7H8	3952550	3940240	Kotas
Benzene	C6H6	3310540	3305350	Kotas
m-Xylene	$C_6H_4(CH_3)_2$	4573100	4573100	*
H2O	H20	11710	3120	Kotas
Argon	Ar	11690	11690	Kotas
CO2	CO2	20140	20140	Kotas
CO	CO	275430	275430	Kotas
NO	NO	89040	89040	Kotas
Nitrogen	N2	720	720	Kotas
Oxygen	O2	3970	3970	Kotas

* Value for 0-xylene from Szargut paper [31] is used here. M-xylene is 1,3- dimethylbenzene, while 0- xylene is 1,2 – dimethylbenzene.

Appendix N

The following table was used in the quality assurance process. Exergy and energy calculations for the wellstream of the 2a - Gas plateau case were compared to that of Rian's [5] wellstream, both of which have the exact same composition.

	Gas plateau Wellstream data				Snøhvit article wellstream data			Ratio	Differential
Specs	Composition:	identical			Composition:	identical			
	Pressure:	1.013	bar		Pressure:	70	bar		
	Temperature:	25	C		Temperature:	0	C		
Exergy	Ch Ex /kmol	921694.1	kj/kmol						
	Mol. Weight	21.4	kg/kmol						
	Ch Ex/kg	43049.7	kj/kg		Ch Ex/kg	43506.8	kj/kg	1.0106	1.06
	TD Ex/kmol	11905.3	kj/kmol						
	Mol. Weight	21.4	kg/kmol						
	TD Ex/kg	556.1	kj/kg		TD Ex/kg	419.5	kj/kg	0.7543	-24.57
Energy	LHV (mole basis)	898941.2	kj/kmol						
	Mol. Weight	21.4	kg/kmol						
	LHV (Mass basis)	41987.0	kj/kg		LHV (Mass basis)	41590.0	kj/kg	0.9905	-0.95
	TD En/kmol	-2223.6	kj/kmol						
	Mol. Weight	21.4	kg/kmol						
	TD En/kg	-103.9	kj/kg		TD En/kg	-130.6	kj/kg	1.2576	25.76

Appendix O

Table of assumptions.

Assumption
No flaring of gas
Equipment pressure losses: LP – 0.3 bar MP – 0.5 bar HP – 1 bar
Pump adiabatic efficiencies: 65 %
Compressor polytropic efficiencies: 75%
Process heating and cooling media: water.
Kinetic and potential energy/exergy of all platform mass flows is negligible.
Exergy reference environment: Temperature – 25 °C, Pressure 1 atm, 60% humidity
Sea and air temperature: 15 °C
Platform behaves as a black box, i.e. there is no heat transfer to or from the platform (apart from that contain within the mass flows)
Both liquid and gas mixtures are ideal mixtures
Complete removal of all hydrocarbons from the produced water stream is achieved.
Absolute entropy of hydrocarbons increases linearly with increasing carbon number.
The chemical exergy of i-butane is equal to that of n- butane.
Internal power transmission losses are accounted for in simulation for all cases
Chemical exergy is calculated for each component assuming it single phase – where that phase is the actual phase that has the highest fraction of the molar flow rate
Sea water is pure H_20
When calculating CO2 production per year, an average of 347 production days per year is assumed

Appendix P

Platform power, heat and cooling duties for each of the power supply options. Oil and gas production rates have also been included, showing the differences in oil and gas production.

Platform Duty table (MW)

	Power Duty	**Heat duty**	**Cooling duty**	**Production rate (BOE*/day)**	
				Oil	Gas
2a - Oil plateau	31.8	31.7	28.3	130000	10012
2b - Oil plateau	32.9	31.5	28.4	130000	10617
2c - Oil plateau	32.0	31.6	28.6	130000	11329
2a - Oil late-life	26.4	12.6	11.0	43333	2818
2b - Oil late-life	26.9	12.5	11.2	43333	3502
2c - Oil late-life	26.6	12.5	11.2	43333	3775
2a - Gas plateau	50.2	15.3	50.4	13440	124588
2b - Gas plateau	51.3	15.1	50.9	13440	126549
2c - Gas plateau	50.9	15.1	51.0	13440	126888
2a - Gas late-life	23.6	7.3	21.5	4368	41299
2b - Gas late-life	24.1	7.2	21.8	4368	42246
2c - Gas late-life	23.9	7.2	21.8	4368	42404

*Where the value of one BOE is assumed to be 5.4GJ.

Appendix Q

Sensitivity analysis of gas turbine par load performance's impact on energy and exergy efficiencies of the cases.

		Act. Load	Adj. Load		Differential	Change in efficiency per 10 % change in GT load
2a_O_p	Load	99.758	80		-19.758	
	GT eff. %	0.3926	0.3594		-0.033	
	Ex	98.279	98.389		-0.110	0.056
	En	99.435	99.544		-0.109	0.055
2a_O_ll	Load	82.74001	100		17.260	
	GT eff. %	0.364429	0.393		0.029	
	Ex	94.289	94.012		0.276	0.160
	En	96.302	96.025		0.277	0.160
2a_G_p	Load	78.77509	98.78		20.005	
	GT eff. %	0.357108	0.391157		0.034	
	Ex	96.761	96.600		0.161	0.080
	En	98.838	98.592		0.246	0.123
2a_G_ll	Load	73.87656	93.88		20.003	
	GT eff. %	0.347673	0.383483		0.036	
	Ex	95.776	95.422		0.354	0.177
	En	98.017	97.661		0.355	0.178