ENERGY AND EXERGY ANALYSIS OF SNØHVIT
- AN LNG PROCESSING PLANT IN NORWAY

Anne Berit Rian[*]**, Helene Lie, Ivar S. Ertesvåg**[†]
Department of Energy and Process Engineering
Norwegian University of Science and Technology
NO-7491 Trondheim, Norway

ABSTRACT

The first plant for LNG export in Europe, which processes natural gas from the Snøhvit field in the Barents Sea, is studied. The plant at Hammerfest in Northern Norway is analyzed using the exergy method. The simulation tool PRO/II (ver. 7.0) with an ad-hoc add-on for exergy is used during the work. It is found that the total exergy of delivered products is 95,0% of the exergy of the feed stream to the plant. The plant is divided into two sub-systems; the processing plant and the combined heat and power plant (CHP). It is found that irreversibilities in the processing plant destroy 1,8% of the feed-stream exergy, while 3,1% is lost in the CHP. The latter includes 2,6% in the gas turbine, 0.2% in the heat-recovery unit, and 0.3% in the emitted exhaust gas. Furthermore, the thermomechanical exergy of the products is found to be 1,4% of the well-stream total exergy. The total energy of the delivered products is 93,3% of the feed-stream energy. The analysis shows that the exergy delivered (in heat and electricity) is 43,5% of the fuel exergy. The differences between the energy accounting and exergy accounting are discussed. Finally, the results are compared to the very same plant localized at higher environmental temperatures (20 and 36 °C).

Key words: exergy, energy, LNG, Snøhvit

1 INTRODUCTION

Natural gas (NG) extraction is expected to increase considerably. The fraction that is transported as liquefied natural gas (LNG) will increase as well, and also in particular, the production in arctic climate.

The Snøhvit (Snow White, named from the well-known fairy tale) field is located in the Barents Sea, about 140 km North-West of Hammerfest in Norway. The gas and condensate field is under development and will be operated entirely by subsea installations, which are placed at the seafloor at 250-345 meters below the sea level. After completion in 2006, the processing plant is going to deliver more than 4 million tonnes of hydrocarbons annually. The products will be mainly LNG and some liquefied petrol gases (LPG) and condensate.

The well stream is brought on shore through a 143 km, two-phase flow pipeline. At the processing plant, components as water, hydrogen sulphide, mercury, nitrogen and carbon dioxide are separated. Nitrogen and water is purified and released to the environment. Carbon dioxide is pressurized and returned to the field through a separate pipeline back and deposited in a sandstone formation at the edge of the field. The well stream will contain 5-8 % of CO_2, which amounts to 0.7 million tonnes annually.

---

[*] Anne.B.Rian@ntnu.no, tel. +47 73 59 35 97, fax +47 73 59 35 80
[†] Ivar.S.Ertesvag@ntnu.no

An LNG plant is interesting for exergy analysis since is spends exergy (fuel, electricity) to remove energy (heat) from the substance. An arctic plant is interesting due to the relatively low ambient temperature. Thus, for an arctic LNG plant both reasons for interest apply.

2 PROCESS DESCRIPTION

A pipeline leads the well-stream from the field to the processing plant [1-3]. H_2O , N_2, CO_2 and MEG (mono ethylene glycol) are separated from the stream. H_2O and N_2 are released into the environment. MEG is added to avoid formation of hydrates, and it is pumped back into the well for reuse. CO_2 is compressed, liquefied, and pumped back into a separate pipeline for deposit. Polluting components such as mercury and sulphur compounds are separated and taken care of, but only H_2S is included in the present analysis. Heavier hydrocarbons are separated from the raw NG stream as condensate and LPG and stored in intermediate tanks at the plant. Finally, the mean NG stream is cooled and liquefied to LNG at -162 °C. Cooling water is taken from open sea.

The on-site combined heat and power plant (CHP) uses processed natural gas, taken from the main stream before liquefaction, in the combustion. It delivers heat and electricity to the process and releases exhaust into the atmosphere. The CHP plant consists of five LM6000PD gas turbines with a low-NOx burner systems. Each GT has an exhaust heat recovery unit with thermal oil as energy carrier for the processing plant. The thermal energy is delivered at three different temperatures. At normal capacity, four gas turbines will be used.

3 METHOLOGY

The analyses of the overall system and the sub-systems are based on the balances of elements, mass, energy, and exergy. For the processes involving hydrocarbon flows, the species, total mass, and energy balances are resolved using the commercially available program PRO/II (ver 7.0) [4]. This program provides enthalpy and entropy differences of the flows. Exergy values are calculated from these differences and the exergy calculator of the program is not used.

For the gas turbine, temperature data is obtained from [5]. The amount of excess air and the flue-gas composition are calculated in a spreadsheet on the basis of the assumed fuel composition and GT-exhaust temperature. The enthalpy and entropy differences for the flue gas flow are calculated by assuming ideal gases, neglecting pressure differences, and integrating

$$d\bar{h} = \bar{c}_P(T)dT \tag{1}$$

$$d\bar{s} = (\bar{c}_P(T)/T)dT \tag{2}$$

over the temperature difference. The overbars denote molar properties. The temperature-dependent functions of the molar heating capacities are obtained from [6].

The thermal enthalpy is determined as the enthalpy at the actual state relative to a specified reference.

$$\bar{h}_{th} = \bar{h}(T,p) - \bar{h}(T_0,p_0) = \bar{h} - \bar{h}_0 \tag{3}$$

The reference is at ambient temperature and pressure (T_0, p_0).The total enthalpy is determined as the sum of the thermal enthalpy and the lower heating value of the substance. All mixtures are regarded ideal mixtures, both in PRO/II and spreadsheet calculations.

For each (sub-)system in steady state, neglecting effects of potential and kinetic energy, the energy balance can be formulated as

$$0 = \dot{Q} - \dot{W} + \sum_{in} \dot{n}_i \bar{h}_i - \sum_{out} \dot{n}_i \bar{h}_i \tag{4}$$

where *Q* is heat transferred to the control volume (CV), *W* is work (actually electric energy) executed on the environment by the CV, n_i and $\bar{h}_i$ are amount of substance and molar enthalpy of flow No. *i*, and the superscript dot indicate rate quantities.

The exergy balance can be developed [7, ,8] from combining the balances of mass, energy and entropy. For a steady state, non-expanding system, neglecting effects of potential and kinetic energy, it can be formulated as

$$0 = \dot{E}^{Q} - \dot{W} + \sum_{in} \dot{n}_i \bar{\varepsilon}_i - \sum_{out} \dot{n}_i \bar{\varepsilon}_i - \dot{I} \qquad (5)$$

where $\dot{E}^{Q}$ is the rate of the transferred exergy by the heat, $\dot{I}$ is the rate of irreversibility (exergy loss, exergy destruction), and ε_i is the total flow exergy [7, 8] of the flow No. *i*. W is the maximum (theoretical) work obtainable from a substance interacting only with a local environment at a specified state. The flow exergy can be split into a thermomechanical ('physical') and a chemical exergy: $\bar{\varepsilon} = \bar{\varepsilon}_{\text{tm}} + \bar{\varepsilon}_0$. The thermomechanical exergy is determined from

$$\bar{\varepsilon}_{\text{tm}} = \bar{h} - \bar{h}_0 - T_0 \left(\bar{s} - \bar{s}_0 \right) \qquad (6)$$

where $\bar{h}_0 = \bar{h}\left(T_0, p_0\right)$ and $\bar{s}_0 = \bar{s}\left(T_0, p_0\right)$ for the relevant flow (mixture).

For a single, gaseous component present in the atmosphere, the chemical exergy is determined as

$$\bar{\varepsilon}_{0,i} = \bar{R}T_0 \ln(p_0 / p_i^e) = -\bar{R}T_0 \ln(x_i^e) \qquad (7)$$

where $\bar{R}$ is the universal gas constant, x_i^e is the mole fraction of the species *i* in the atmosphere, and p_i^e is the corresponding partial pressure. For other species, data for chemical exergy are obtained from Kotas [7]. These data are given at a reference state of 1 atm, 25 ºC $\left(T^{\text{o}}, p^{\text{o}}\right)$, and corrected for deviating ambient conditions according to [8]

$$\bar{\varepsilon}_{0,i} = \bar{\varepsilon}_i^{o} \frac{T_0}{T^{\text{o}}} + \bar{h}_{\text{LHV}}^{\text{o}} \frac{T^{\text{o}} - T_0}{T^{\text{o}}} + T_0 \bar{R} \sum_{j \neq i} \nu_j \ln \frac{x_j^{o}}{x_{j,o}} \qquad (8)$$

where $\bar{\varepsilon}_i^{o}$ and $\bar{h}_{\text{LHV}}^{\text{o}}$ are the molar chemical exergy and the molar lower heating value, respectively, determined at 1atm, 25 ºC., The index *j* denotes the co-reactants and the products of the reference reaction. The chemical exergy of a gaseous mixture is determined from

$$\bar{\varepsilon}_{0,\text{mix}} = \sum x_i \bar{\varepsilon}_{0,i} + \bar{R}T_0 \sum x_i \ln x_i \qquad (9)$$

where x_i is the mole fraction of species *i* in the mixture.

The energy and the exergy efficiencies can be defined as the ratio of "useful" output to the input for a specified system. Such parameters may be convenient to use if the "output" and the "input" is carefully defined. As the (sub-)systems of the present analysis are assumed steady-state steady-flow, such efficiencies are calculated using rate quantities.

4 PRESENT PREDICTIONS

The systems of analysis are shown in Fig.1. The mass flows and compositions are chosen to be in balance with respect to mass and elements in the CHP and to mass, individual species, and LHV for the processing plant. The total plant is divided into two subsystems; the processing plant and the CHP. Within the latter, the gas turbine (GT) and the heat-recovery unit (HRU) can to a large extent be separated in the analysis. The chosen system and sub-system boundaries are based on accessibility of data and the possibility of verifying the different mass flows.

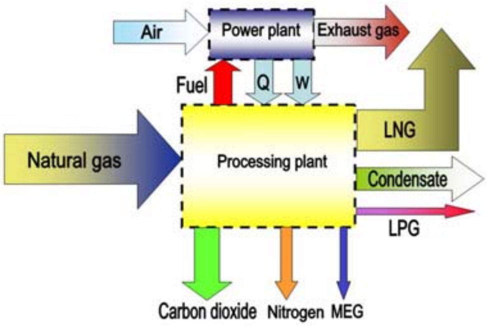

Figure 1 Processing plant and combined heat and power plant: dashed lines indicates the chosen control volume

The flow rates, temperatures, and pressures for the inflows and outflows are given in Table 1 and 2 for the two subsystems [1]. The state of the exhaust gas flow in the CHP is given both before and after the heat exchange with the heat-transporting media (hot oil) in the HRU.

The compositions of the wellstream feed (raw NG) and the main product, LNG are shown in Table 3. These compositions are possible compositions. Due to business and competition, the developer of the plant is reluctant to expose exact, actual compositions of the flows. On the other hand, the composition of the wellstream, and hence, of the products will change over time.

Table 1 Flow rates, temperatures and pressures of the flows into and out of the processing plant (PP).

PP	FR [kg/s]	T [K]	p [bar]
Feed	227,39	273,15	70,00
LNG	151,17	110,95	4,90
LPG	7,95	244,95	8,65
Condensate	24,61	290,25	9,58
Fuel to CHP	10,72	284,15	66,25
CO2	22,36	325,15	211,00
MEG	3,22	273,25	70,00
Nitrogen	5,40	290,15	1,01

Table 2 Flow rates, temperatures and pressures for the combined heat and power plant

CHP	FR [kg/s]	T [K]	p [bar]
Fuel	10,72	284,15	66,25
Air	481,74	277,15	1,01
Exhaust (GT)	492,46	725,15	1,01
Exhaust (stack)	492,46	438,15	1,01

The fuel to the CHP is assumed to have the same composition as LNG. The electric power delivered by the CHP is set to 184 MW. The heat recovery unit is designed to deliver heat in hot oil at three temperature levels; 51,55 MW at 533 K, 81,35 MW at 465 K, and 9,55 MW at 418 K. The given energy rates are the heat rates released from the hot oil when cooled from the given temperatures. A constant specific heat capacity of 2,6 kJ/(kg·K) is assumed for the oil.

The cooling water is assumed to be available at 4 °C, which is a typical and close to constant year-round temperature at 50–100 m sea depth in the area. Thus, this is the chosen ambient temperature for the analysis, that is, for the ambient air as well. The atmospheric pressure is set to 1 atm. In the exergy calculations, the air is assumed to have a relative humidity (RH) of 70%. Kotas' reference composition of dry air [7] is chosen, and the water content is calculated based on the chosen RH.

The chemical exergies of atmospheric gases are determined with reference to the specified atmosphere. For other substances, the values of chemical exergy are taken from Kotas [7], and then corrected for the lower ambient temperature and humidity according to the procedure described above. The effect of different ambient temperature on heating values is much less, and is neglected in the present analysis. Thus, the lower heating values determined at 25 °C are used. The mixtures are assumed ideal mixtures with respect to enthalpy (including lower heating values).

Table 3 Composition of the feed (raw natural gas) and the LNG.

Substance	NG [%]	LNG [%]
Methane	80,92 %	91,88 %
Etan	4,77 %	5,32 %
Propane	2,42 %	1,93 %
n-butane	0,60 %	0,10 %
i-butane	0,38 %	0,12 %
n-pentane	0,23 %	0,00 %
i-pentane	0,27 %	0,00 %
n-hexane (g)	0,32 %	
n-heptane (l)	0,35 %	
n-octane (l)	0,29 %	
Hydrogen sulphide	0,00 %	
Water	1,04 %	
Carbon dioxide	4,84 %	0,01 %
Nitrogen	2,40 %	0,64 %
N- nonane	0,12 %	
Benzene (l)	0,06 %	
Toluene (l)	0,08 %	
M xylene	0,05 %	
N - decane	0,12 %	
N - undecane	0,05 %	
N - dodecane	0,05 %	
N - tridecane	0,04 %	
N - tetradecane	0,03 %	
N - pentadecane	0,02 %	
N - heksadecane	0,01 %	
N - heptadecane	0,01 %	
N - oktadecane	0,01 %	
N - nonadecane	0,01 %	
N - eicosane	0,01 %	
MEG	0,49 %	
Sum	100 %	100 %

The chemical exergy is calculated with reference to the atmosphere. Special care has to be taken when inspecting the values for substances that occur in liquid state, that is, captured CO_2 compressed and liquefied for deposit, and LNG: For consistency throughout the entire process, the chemical exergies of these substances were determined as if they were gaseous. Then the negative exergy due to condensing was included in the thermo-mechanical exergy. Accordingly, the total exergy might be less than the chemical exergy. Alternatively, the phase-change exergy could have been included in the chemical exergy. In either case, the total exergy of the substance will be the same.

The ratio of the chemical exergy to the LHV for the given composition of LNG is 1,04, which is a usual value for traded natural gas. For the raw NG (feed), the ratio is slightly higher (1,05). This is partly due to the amounts of heavier hydrocarbons. In addition, the amounts of nitrogen and carbon dioxide contribute to the chemical exergy but have no effect on the heating value except dilution

Compression of CO_2

Although the full specifications of this sub-process are not available, the exergy required for compression the fluid can be estimated. The calculations are based on the results from [9] of a three-step intercooled compression of CO_2 from 1 atm to 60 bar, condensing, and subsequent pumping to 200 bar.

5 RESULTS AND DISCUSSION

5.1 Processing plant

The flow rates of mass, the amounts of carbon, and the amounts of substances for the processing plant are shown in Table 4 and 5. The enthalpy and the exergy are shown as specific values and as rate figures. The enthalpies are split into an LHV and a thermal enthalpy. Also the exergies are split into a chemical exergy and a thermomechanical exergy (see above).

5.1.1 Energy and exergy analysis

The enthalpies of the exchanged flows are supposed to balance the heat and electricity delivered by the CHP diffuse heat losses to the environment, and cooling by the cooling water. As nitrogen and water separated from the NG are simply released to the atmosphere, these flows are also included in the loss.

Table 4 Processing plant – energy analysis

		lhv	**h_{th}**	**lhv**	**H_{th}**	**H_{TOT}**
	molC/s	MJ/kg	kJ/kg	MW	MW	MW
Feed	13,00	41,59	-130,61	9457,82	-29,70	9428,12
LNG	9,43	49,06	-855,99	7416,35	-129,40	7286,95
LPG	0,54	46,07	-465,20	366,08	-3,70	362,39
Cond	1,74	44,48	28,22	1094,72	0,69	1095,41
Fuel	0,67	49,06	-68,82	525,71	-0,74	524,97
CO2	0,51	0,00	-184,14	0,00	-4,12	-4,12
MEG	0,10	17,06	-3,44	54,91	-0,01	54,90
Nitrogen	0,00	0,00	13,45	0,00	0,07	0,07
Water	0,00	0,00	0,00	0,00	0,00	0,00
H2S	0,00	27,77	-379,37	0,05	0,00	0,05

Table 5 Processing plant – exergy analysis

		ε^o	**ε_{th}**	**E^o**	**E_{th}**	**E_{TOT}**
	molC/s	kJ/kg	kJ/kg	MW	MW	MW
Feed	13,00	43506,78	419,45	9892,84	95,38	9988,21
LNG	9,43	51158,85	873,08	7733,63	131,98	7865,61
LPG	0,54	48624,78	50,89	386,41	0,40	386,81
Cond	1,74	47273,88	2,04	1163,54	0,05	1163,59
Fuel	0,67	51158,85	527,62	548,20	5,65	553,85
CO2	0,51	425,23	205,51	9,51	4,59	14,10
MEG	0,10	19436,11	7,33	62,57	0,02	62,60
Nitrogen	0,00	23,89	0,31	0,13	0,00	0,13
Water	0,00	661,67	0,00	1,30	0,00	1,30
H2S	0,00	23937,37	190,27	0,04	0,00	0,04

The heat delivered from the CHP is treated as exchange of hot oil between the subsystems. The rate heat delivered from the CHP, i.e. the difference of thermal energy, is 142,45 MW and the corresponding rate of exergy is 56,79 MW. The exergy loss due to heat transfer from hot oil to the process is included in the process-plant analysis, while the loss due to heat transfer from flue gas to hot oil in the HRU is included in the CHP analysis.

The delivered products from the processing plant are the tradable products (LNG, LPG, condensate) and the fuel to the CHP. The re-used MEG should also be regarded as a useful product. The total enthalpy flow rates of these products are 9324,6 MW. Thus the energy output is 95,6% of the total input in the feed stream, the heat and the electricity.

The delivered products carry a total flow-exergy rate of 10032,5 MW, which is 98,1 % of that of the input comprising raw NG feed, heat, and electricity. For these products, the thermomechanical exergy is 1,4 % of the total exergy, and the remaining is chemical exergy. Furthermore, the separated and compressed CO_2 for deposit can in a sense be regarded as a useful product. This adds another 14,1 MW (0.1% of the feed) to the useful output.

The total losses of the processing plant summarizes to 429,9 MW of energy and 182,4 MW of exergy. This corresponds to 4,6% and 1,8%, respectively, of the energy and exergy of the incoming feed stream.

5.1.2 Compression of CO_2

The calculated results for the CO_2 compression in [9] imply a specific work of 366 kJ/kg CO_2 or 8,2 MW in total and 205,53 kJ/kg of thermomechanical exergy or 4,59 MW for the present case. For technical reasons, CO_2 is always removed from natural gas before liquefaction. Thus, the separation cost is not particular for the plant of the present analysis. However, other plants simply release the CO_2 to the atmosphere.

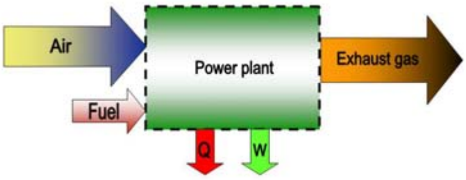

Figure 3 Combined heat and power plant: dashed lines indicates the chosen control volume

5.2 Heat and power plant

This subsystem can be treated in two sections: First, the fuel is burned with compressed air in the gas turbine (GT), which produces all the electric energy. Second, the exhaust from the GT is used in the heat-recovery unit. This CHP delivers all the heat and electricity needed to operate the processing plant. The “heat” in this context is determined as the sum of rates of enthalpy differences between out-flowing and inflowing streams of hot oil. The associated exergy is the sum of the corresponding differences in rates of flow exergy. No phase change occurs in the hot oil.

5.2.1 Energy and exergy analysis

The flow rates, specific and rate values of enthalpy and exergy of the flows are shown in Table 6 and 7. It can be noted that due to pressurization, the gaseous fuel has a thermomechanical exergy that adds 1,0 % to the chemical exergy. Contrary to this, the enthalpy value is slightly reduced at an elevated pressure (due to real-gas effects).

Table 6 Heat and power plant – energy analysis

	lhv	**h_{th}**	**lhv**	**H_{th}**	**H_{TOT}**
	MJ/kg	kJ/kg	MW	MW	MW
Fuel	49,06	-68,82	525,71	-0,74	524,97
Air	0,00	0,00	0,00	0,00	0,00
Exhaust (GT)	0,00	489,32	0,00	240,97	240,97
Exhaust (stack)	0,00	170,91	0,00	84,17	84,17

Table 7 Heat and power plant – exergy analysis

	ε^o	**ε_{th}**	**E^o**	**E_{th}**	**E_{TOT}**
	kJ/kg	kJ/kg	MW	MW	MW
Fuel	51158,85	527,62	548,20	5,65	553,85
Air	0,00	0,00	0,00	0,00	0,00
Exhaust (GT)	28,49	198,17	14,03	97,59	111,62
Exhaust (stack)	28,49	36,16	14,03	17,81	31,84

The net electric power delivery from the plant, 184 MW, is 35,0 % of the rate of lower heating value (LHV) of the supplied fuel. The rate of heat delivery, 142,45 MW, is 27,1% of the LHV rate, or 59,1% of the thermal-enthalpy rate of the flue gas exiting from the GT. The total delivery, i.e. electricity and heat, is 62,1% of the LHV.

The rate of exergy associated with heat is 56,79 MW, which is 50,9% of the flow exergy of the GT exhaust. The total rate of exergy delivered from the CHP is then 240,8 MW or 43,5% of the rate of total flow exergy of the supplied fuel.

The energy losses are thermal energy in flue gas to the stack, diffuse heat losses, auxiliary consumption, mechanical losses, etc. This summarizes to a rate of 198,5 MW, which is 37,8% of that of the supplied fuel. The rate of the total exergy losses are 313,1 MW, which is 56,5% of the total flow exergy of the supplied fuel

The GT exergy losses can be estimated to 258,2 MW. Thus, the main contributors to this exergy loss, is exergy destruction by the combustion (typically one-third of the fuel exergy) and heat transfer over large temperature differences between the exhaust and the hot-oil system. The rejected flue gas carries only 5,8% of the fuel exergy.

When the processing plant in some years is expanded, other solutions for the combined heat and power plant ought to be investigated. By using a steam cycle for the heat recovery unit, the temperature profiles may be better matched to each other. Such a system may include back-pressure steam turbines, where the high temperature heat is transformed into power, and the heat demand is by heat at lower temperatures.

5.3 Overall plant

The energy and exergy analyses of the entire system (both processing plant and heat and power plant) give an energy loss of 628,5 MW, which is 6,7% of the incoming flow and an exergy loss of 495,5 MW which is 5,0% of the incoming flow. Nitrogen and exhaust are both regarded as parts of the losses as the energy and exergy are not utilized.

The entire system has got an energy efficiency of 93,3% and an exergy efficiency of 95,0 %. LNG, condensate, LPG, MEG and carbon dioxide are regarded as products in the exergy analysis, but the latter is excluded from the product when calculating the energy efficiency due to the negative enthalpy. The rate of thermomechanical exergy of the products is 137 MW or 1,4% of the total exergy rate of the wellstream.

These figures are high compared to e.g. a power plant, a paper mill or an aluminum factory. The reason is, of course, which the “useful output” is hydrocarbons that are not chemically changed in the process, just separated and cooled.
One interesting figure, although hard to determine and not available from the present analysis, is the increased chemical exergy due to separation of substances. This increased exergy, in addition to the thermomechanical exergy due to low temperature and elevated pressure, may be regarded as the “useful output” of an LNG plant. In such an accounting, the “input” will be the exergy of the consumed part of the wellstream.

The benefits of low ambient temperature for a power plant are well known: Colder air reduces the work required for air compression. Colder cooling water reduces the condenser pressure and increases the pressure ratio for steam turbines. The significance of low ambient temperature for an LNG plant can be illustrated with the following estimates: For condensing of a pure substance at 111 K (saturation temperature for pure methane at 1 atm), the heat removed is independent of the ambient temperature. However, the required minimum exergy is 16% larger for an ambient temperature at 303 K compared to an ambient temperature at 277 K. If a substance (with, for the estimate, a constant specific heating capacity and no phase change) is cooled from ambient temperature to 111 K, the heat removed is 16 % larger for an ambient temperature at 303 K compared to an ambient temperature of 277 K. The required (minimum) exergy is, however, 29 % larger.

The question remains of how to compare performances of plants located in different climates. One option is to compare the fuel consumption (mass or LHV) per unit of delivered LNG or other products. This metric is obvious in the sense that a unit of consumed fuel is a unit of degraded natural recourse. However, even if the cold-climate plant spends less fuel for its operation, the warm-climate plant may still have a better thermodynamic performance given the natural constraints. In the latter case, the amount of avoidable resource degradation is lower

5.4 Environmental temperature

The analysis is repeated for ambient temperatures at 20 ºC and 36 ºC. The ambient RH is maintained at 70% (i.e. higher absolute humidity). All mass flow rates, compositions and states of the flows are maintained, except that the feed temperature is set to 4 K below ambient. Higher T_0 both increase the chemical exergy (at constant RH) and the thermo-mechanical exergy of cooled substances. Table 8 shows some key exergy results from the three cases.

Table 8 Results for different ambient temperatures.

Exergy of.....	to exergy in	4 °C	20 °C	36 °C
(LNG+LPG+Cond.)	feed	94,90 %	94,99 %	94,97 %
(work +heat)	fuel	43,48 %	42,71 %	41,93 %
losses in PP	feed	1,83 %	1,68 %	1,65 %
losses in CHP	fuel	56,52 %	57,29 %	58,07 %
lost to stack	fuel	5,75 %	4,77 %	3,88 %
lost in GT	fuel	46,63 %	48,23 %	49,71 %

CCCC

6 CONCLUDING REMARKS

The energy and exergy analysis assesses the effectiveness of the Snøhvit LNG processing plant in Northern Norway. The overall system from feed (raw natural gas) to liquefaction has got an energy efficiency of 93,3% and an exergy efficiency of 95,0%. In order to improve the facility the parts which represents the greatest losses and are possible to improve, need to be chosen. The liquefaction is the main process of the plant, thus the other processes need to adjust to this part. The heat distribution system in the combined heat and power plant is an obvious choice as the energy loss is 21,8%, of the incoming flow, while the exergy loss is 50,3% of the incoming flow. Thus the potential is far from utilized. Further calculations show that only 51,5 % of the exergy in the exhaust is transferred to the hot oil system. The exergy efficiency of this sub-system is only 43,6%. An alternative solution for the heat distribution system ought to be considered when expanding the plant. By using a steam cycle the exhaust may also produce additional electricity. In addition, an economical analysis is necessary in order to decide whether the alternatives are profitable.

REFERENCES

[1] Lie, H. *LNG from well to consumer: An analysis of the LNG chain*. Master thesis, Energy and Processs Engineering, Norwegian University of Science and Technology, Trondheim, Norway, 2005.

[2] Statoil. *Impact assessment for Snøhvit*, (In Norwegian). April 2001. http://www.statoil.com

[3] Statoil. *Snøhvit LNG - Application for permit of discharges*. , (In Norwegian). 2001. http://www.statoil.com

[4] Simsci Inc., Pro/II v.7.0, http://www.simsci.com

[5] Gas turbine world

[6] Moran, M.J., Shapiro, H.N. *Fundamentals of engineering thermodynamics*: 5th ed. John Wiley & Sons, 2004.

[7] Kotas T.J. *The exergy method of thermal plant analysis*. 2nd ed. Malabar, Florida: Krieger Publishing Comapany, 1995.

[8] Szargut, J., Morris, D.R., Steward, F.R: *Exergy analysis of thermal, chemical and metallurgical processes*. Hemisphere, New York, 1988

[9] Ertesvåg, I.S., Kvamsdal, H.M., Bolland, O. *Exergy analysis of a gas-turbine combined cycle power plant with precombustion* CO_2. Energy. 2005;30(1):5-39