Thermodynamic Performance Indicators for Offshore Oil and Gas Processing: Application to Four North Sea Facilities

Mari Voldsund, Norwegian University of Science and Technology; **Tuong-Van Nguyen** and **Brian Elmegaard,** Technical University of Denmark; and **Ivar Ståle Ertesvåg** and **Signe Kjelstrup,** Norwegian University of Science and Technology

Summary
Well-defined performance indicators can motivate optimal operation of offshore oil and gas platforms. We evaluate several thermodynamic performance indicators presented in the literature according to three criteria: Thermodynamic performance indicators should evaluate the use of technically achievable potential, they should evaluate the use of theoretical potential, and they should evaluate the total use of energy resources. The performance indicators are tested on four North Sea facilities, and the results are discussed. We recommend the use of a set of indicators for a thorough evaluation of oil and gas platforms—the best-available-technology efficiency on an exergy basis, a task exergy efficiency, and the specific exergy destruction.

Introduction
Offshore oil and gas extraction was responsible for approximately 20% of the total gross greenhouse-gas emissions in Norway in 2011 (Statistics Norway 2013). These emissions were mainly caused by the natural-gas and diesel-oil combustion required on offshore facilities to meet the on-site power and heat demand. Reduction of carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions on oil and gas offshore facilities is a challenge because performance and reliability requirements, as well as space limitations, lead to conservative choices of technology. The overall design of such installations is similar for all platforms. However, each oil field has specific natural characteristics (e.g., gas/oil and water/oil ratios, pressure and temperature levels, reservoir-fluid properties), each platform has particular design setups (e.g., number of compression trains, export specifications, unit inventory), and different oil-recovery strategies (e.g., seawater or gas injection, pressure depletion) are used. Moreover, the production flows on-site vary significantly over the lifespan of the field, which creates challenges in maintaining efficient processing. Evaluation of such systems is complicated, and performance indicators should be chosen with care to make a meaningful comparison.

Svalheim and King (2003) pointed out that the performance of an offshore platform can be measured by the specific volumes of CO_2 emitted or of gas consumed onsite (fuel, venting, and flaring) and by the specific power consumption on a net-produced oil-equivalent basis. However, it was underlined that these metrics can be misrepresentative and favor facilities that process oil and gas with higher energy contents. In addition, platforms with certain operating conditions may be favored because they can more easily achieve their tasks with low power consumption.

Possible other approaches, applied in similar research fields, are to compare the overall energy use with that used when integrating state-of-the-art technologies (Margarone et al. 2011) or during optimal energy management (Svalheim and King 2003). These allow benchmarking of the energy required and assessment of further potentials for energy savings. However, as also emphasized in Margarone et al. (2011), energy accounting does not provide information on the extents and locations of the thermodynamic inefficiencies that are present in the overall plant and its subsystems. Such information is given by an exergy analysis (Bejan et al. 1996). A few exergy analyses of oil and gas platforms are reported in the literature, with case studies conducted by De Oliveira and Van Hombeeck (1997) on a Brazilian platform, by Voldsund et al. (2013a) on a Norwegian platform, a comparison on four Norwegian platforms (Voldsund et al. 2014), and a generic analysis by Nguyen et al. (2013). It was pointed out that field conditions, such as gas/oil ratios, feed-pressure levels, and outlet-pressure specifications in the products, have a high impact on the fuel consumption. Furthermore, operation away from the nominal design point and inefficient compression give rise to additional exergy destruction, and thus fuel consumption that could have been avoided. Recommendations for improvement were discussed in these works, but the literature appears to contain no systematic discussions on thermodynamic performance indicators that consider energetic and exergetic aspects of oil and gas platforms and allow a rational comparison. The present work aims to help address this gap by a further study of the four platforms simulated by Voldsund et al. (2014) that follows these steps: (1) presentation of three criteria for suitable performance indicators, (2) definition and investigation of energy- and exergy-based indicators, and (3) comparison of the four oil and gas installations and discussion of the parameters. The present work is the continuation of ongoing research projects, the preliminary results of which were presented in Voldsund et al. (2013b).

The paper is structured as follows. First, an introduction is given to the concept of exergy. Criteria for suitable thermodynamic performance indicators are given before the indicators themselves are presented. This is followed by the results obtained for each platform, with the different indicators, and a discussion of the relevance of these criteria. Finally, concluding remarks are given.

Methodology
Exergy Analysis. Exergy analysis derives from both the first and second laws of thermodynamics, and *exergy* is defined as the maximum obtainable work that can be extracted from a matter in interaction with the environment. This leads to a higher value for thermal energy, with temperatures far above or below the ambient temperature rather than close to it. Exergy analysis differs from energy analysis, which derives from the first law of thermodynamics only and treats all forms of energy as equivalent (Kotas 1995). Energy accounting does not provide information on the extents and locations of thermodynamic inefficiencies present within the plant, at the contrary of an exergy accounting (Margarone et al. 2011).

Exergy Accounting. Exergy is not conserved in nonideal processes and is destroyed to a certain extent (Kotas 1995; Moran

Original SPE manuscript received for review 4 January 2014. Revised manuscript received for review 16 June 2014. Paper (SPE 171565) peer approved 4 August 2014.

1989). The systems investigated within this study can be considered open systems operating at steady-state conditions. The destroyed exergy, expressed here as an exergy destruction rate $\dot{E}_d$, is then the difference between the rates of exergy entering a system ($\dot{E}_{in}$) and the exergy leaving it ($\dot{E}_{out}$) through mass flows, work, and heat transfer:

$$\dot{E}_d = \sum \dot{E}_{\text{in}} - \sum \dot{E}_{\text{out}} = \dot{E}_W + \dot{E}_Q + \sum_j \dot{m}_j e_j \text{ . ... (1)}$$

Symbols $\dot{E}_W$ and $\dot{E}_Q$ are the rates of exergy accompanying work and heat, respectively, and $\dot{m}_j$ and e_j are the mass-flow rate and the specific exergy of the stream of matter *j*, respectively. This exergy balance can be expressed as

$$\dot{E}_p = \dot{E}_f - \dot{E}_d - \dot{E}_l \text{ , ...(2)}$$

where (Tsatsaronis 2007)

- $\dot{E}_p$ is the rate of product exergy, which represents the desired results, expressed in terms of exergy, generated by the system, process, or component of consideration.
- $\dot{E}_f$ is the rate of fuel/used exergy, which illustrates the resources expended to drive the system of interest and to generate the desired product.
- $\dot{E}_d$ is the rate of destroyed exergy, which represents the thermodynamic inefficiencies of a system (entropy generation) because of the irreversibilities taking place within its boundaries (internal).
- $\dot{E}_l$ is the rate of lost exergy, which illustrates the thermodynamic inefficiencies of a system caused by the transport of exergy with energy and material streams to the environment (external).

The exact expression for each of these terms depends on the system investigated.

Exergy Transfer. The exergy flow rate transferred to the system with work is equal to its energy:

$$\dot{E}_W = \dot{W} \text{ , ...(3)}$$

while it depends on the system and environmental temperatures when transferred with heat. For temperatures above the environmental,

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_j}\right)\dot{Q} \text{ . ...(4)}$$

The symbols T_0 and T_j are, respectively, the temperatures of the environment and at the boundary of the system under study, and $\dot{Q}$ and $\dot{W}$ correspond to the energy transfer rates by heat and work, respectively.

The exergy flowing with a stream of matter e can be expressed as the sum of the kinetic e^{kin}, the potential e^{pot}, the physical e^{ph}, and the chemical e^{ch} components:

$$e = e^{\text{kin}} + e^{\text{pot}} + e^{\text{ph}} + e^{\text{ch}} \text{ . ...(5)}$$

Specific physical exergy accounts for temperature and pressure differences with the ambient conditions (T_0, p_0) without considering any changes in chemical composition. It can be expressed as

$$e^{\text{ph}} = (h - h_0) - T_0(s - s_0) \text{, ...(6)}$$

where h and s are the enthalpy and entropy calculated at the stream conditions, respectively, and h_0 and s_0 are the same-state variables at environmental temperature and pressure. Similarly, the specific chemical exergy accounts for the maximum obtainable work resulting from the differences in chemical composition and environmental composition, while maintaining the same temperature and pressure. It is expressed as

$$e^{\text{ch}} = \underbrace{\sum_i x_i \bar{e}_i}_{\text{I}} + \underbrace{\left[\left(h_0 - \sum_i x_i h_{i,0}\right) - T_0\left(s_0 - \sum_i x_i s_{i,0}\right)\right]}_{\text{II}} = \underbrace{\sum_i x_i \bar{\bar{e}}_i}_{\text{III}} \text{,}$$

$$\text{...(7)}$$

where Term I represents the chemical exergy of the components in pure state, with x_i being the mass fraction and $\bar{e}_i$ being the specific chemical exergy on a mass basis. Term II corresponds to the decrease of chemical exergy because of mixing effects (namely, the exergy of mixing) with $h_{i,0}$ being the mass chemical enthalpy of the pure component i and $s_{i,0}$ being the corresponding mass entropy at environmental conditions. Term III denotes the chemical exergy of the components in the mixture, with $\bar{\bar{e}}_i$ the specific chemical exergy of the component i in the mixture. The specific potential and kinetic exergies are assumed negligible in comparison with the chemical and physical exergies.

Thermodynamic Performance Indicators. The present study is among the first studies on the thermodynamic performance of offshore oil and gas processing. The primary goal is to investigate the usefulness of several indicators. We consider that a useful indicator should

1. Evaluate whether the technically achievable potential is used. A useful indicator should answer whether the performance of the platform could be enhanced further, considering all improvements that could be brought to the system with the best-available technologies (BAT). These improvements can be related to the use of more-efficient equipment, such as compressors and pumps, or to a better process integration.
2. Evaluate whether the theoretically achievable potential is used. A process with a given set of boundary conditions, such as temperatures, pressures, compositions, or flow rates, can never consume less exergy than in the reversible case. This case sets an upper limit for energy efficiency, and a useful indicator should answer whether the process under consideration is far from this limit. This criterion favors indicators that motivate the use of both BAT and research and development of new solutions.
3. Evaluate the total use of energy resources. Oil and gas platforms may operate under very different conditions (e.g., different feed compositions, temperatures, or pressures). The total use of energy resources for extraction of petroleum will vary significantly across oil fields, even when they all are run as efficiently as possible. The total use of energy resources should be a part of the evaluation of the performance of oil and gas platforms. Such indicators would motivate the extraction of the least-energy-demanding petroleum resources.

The first two criteria focus on the use of potentials (i.e., the technically and theoretically achievable potentials), while the third criterion is different because it focuses on quantification of the energy resources used only.

To satisfy each criterion, the indicator should be sensitive to the improvements made in the process with respect to the criterion in question. A set of indicators may be necessary to assess the different aspects of the performance of an oil and gas platform.

Among thermodynamic indicators, we distinguish those that are based on energy and those that are based on exergy. They describe different properties of a process, and definitions are provided in the following subsections for some typical and some special indicators.

Energy-Based Indicators. There exist several energy-based performance indicators for industrial processes. One indicator already in use in the oil and gas sector is the energy used per unit of oil and gas exported. When investigating only the oil- and gas-processing part of the platform, the energy use corresponds to the use of power and heat in the process. We name this factor the *specific energy use*. It can be given per standard volume of oil equivalent export rate $\dot{V}_{\text{export}}$:

$$EnU_{\text{volume}} \equiv \frac{\dot{W}_{\text{in}} + \dot{Q}_{\text{in}}}{\dot{V}_{\text{export}}} \text{ .} \quad (8)$$

However, as emphasized by Svalheim and King (2003), the calorific value of the oil and gas produced on-site differs with the characteristics of the oil field. It is therefore relevant to also calculate the specific energy use per energy exported:

$$EnU_{\text{energy}} \equiv \frac{\dot{W}_{\text{in}} + \dot{Q}_{\text{in}}}{L\dot{H}V_{\text{export}}} \text{ ,} \quad (9)$$

where $L\dot{H}V_{\text{export}}$ is the lower-heating-value export rate. In this work, the lower heating value is considered in the expression of the EnU_{energy} indicator because it is the norm in the Norwegian oil and gas industry.

These energy-performance indicators provide limited information on the performance of the processes running on the offshore platform, as discussed by Svalheim and King (2003) and similarly by Margarone et al. (2011). In addition, they do not address the different qualities of power and heat energy. They may not allow a fair comparison of different facilities because they likewise do not consider the specific conditions of each platform, such as

- The field conditions (e.g., initial pressure, temperature, and well-fluid composition)
- The specifications of the oil- and gas-processing system (e.g., the export pressures of the oil-pumping, gas-recompression, and treatment sections)
- The possible additional processes (e.g., condensate treatment, seawater injection, produced-water treatment, crude-oil heating, gas dehydration, and purification)

Margarone et al. (2011) suggested evaluating the plant performance of an upstream gas-treatment facility by comparing it against the performance reachable with the BAT. The proposed indicator, called the *BAT efficiency* (η_{BAT}), is defined as the ratio of the energy content of the fuel required on-site, with the BAT for compression and pumping, to the energy content of the fuel consumed on-site in the reference case. When looking only at the oil- and gas-processing part of an oil platform, this corresponds to

$$\eta_{\text{BAT}} \equiv \frac{\dot{W}_{\text{BAT,in}} + \dot{Q}_{\text{BAT,in}}}{\dot{W}_{\text{in}} + \dot{Q}_{\text{in}}} \text{ ,} \quad (10)$$

where the subscript BAT denotes that the variable is for a process with BAT.

The state-of-the-art components are assumed to be

- Intercooled compressors suitable for the relevant flow rates (i.e., without gas recirculation to prevent surge) with an isentropic efficiency of 85% and intercoolers with a maximum discharge temperature of 100°C (if intercooling does not cause formation of liquid droplets) and optimal pressure ratios in the compression trains
- Pumps suitable for the relevant flow rates with efficiencies of 85%

Exergy-Based Indicators. An exergy-based indicator corresponding to the specific energy use is the *specific exergy use*. It can be given per standard volume of oil equivalent exported,

$$ExU_{\text{volume}} \equiv \frac{\dot{E}_{W,\text{in}} + \dot{E}_{Q,\text{in}}}{\dot{V}_{\text{export}}}, \quad (11)$$

or per exported exergy $\dot{E}_{\text{export}}$,

$$ExU_{\text{exergy}} \equiv \frac{\dot{E}_{W,\text{in}} + \dot{E}_{Q,\text{in}}}{\dot{E}_{\text{export}}} \text{ .} \quad (12)$$

The specific energy use and the specific exergy use are both sensitive to reductions in thermodynamic irreversibilities taking place within the studied system. An indicator that measures this property directly is the *specific exergy destruction* (*ExD*). It can also be calculated per standard volume of oil equivalent exported,

$$ExD_{\text{volume}} \equiv \frac{\dot{E}_d}{\dot{V}_{\text{export}}} \text{ ,} \quad (13)$$

or per exported exergy,

$$ExD_{\text{exergy}} \equiv \frac{\dot{E}_d}{\dot{E}_{\text{export}}} \text{ .} \quad (14)$$

The term *exported exergy* in Eqs. 12 and 14 refers to the exergy content of oil and gas transported to the shore, and should not be confused with the term *product exergy*.

The *thermodynamic performance* of a given system can be expressed by calculating any of these exergetic indicators. The *ExD* indicator of Eq. 14 describes in a straightforward manner the magnitude of the thermodynamic irreversibilities taking place within the system boundaries.

In this work, we calculate two different types of exergy efficiency found in the literature. The *total exergy efficiency* (Lior and Zhang 2007), also called the *overall exergy efficiency,* is defined as the ratio of all exergy outputs of the system to all exergy inputs. We choose to use the formulation in which only the exergy of the output streams that are useful (e.g., exported oil and gas) is taken into account as exergy output, while the exergy of the waste outputs (e.g., cooling water and flared or vented gases) is regarded as lost (Fratzscher et al. 1986; Wall 2004):

$$\varepsilon_{\text{total}} \equiv \frac{\sum_{\text{out},u} \dot{E}_{\text{out},u}}{\sum_{\text{in}} \dot{E}_{\text{in}}} = 1 - \frac{\sum_{\text{out},l} \dot{E}_{\text{out},l} + \dot{E}_d}{\sum_{\text{in}} \dot{E}_{\text{in}}} \text{ .} \quad (15)$$

Subscript u denotes useful streams, while subscript l denotes streams with exergy that is lost. This distinction is of particular importance when the exergy of the waste streams, such as produced water and flared gas, is significant. This efficiency formulation is unambiguous and can be applied to any type of plant or process. However, the total exergy efficiencies take into account the exergy flows entering and exiting a system without considering whether they are used in thermodynamic conversions. They do not consider the purpose of operating the system under consideration. This is the idea behind the definition of *task exergy efficiency*.

The task exergy efficiency is defined as the ratio of the product exergy of the plant to the fuel/used exergy. In the exergy analysis of the Brazilian oil platform performed by De Oliveira and Van Hombeeck (1997), the product exergy was defined as the increase in physical and chemical exergy of the feed streams:

$$\dot{E}_p^* \equiv \sum_k \dot{E}_k - \dot{E}_{\text{feed}} \text{ ,} \quad (16)$$

where subscript k denotes product stream k, while subscript "feed" denotes the feed streams of the platform. The fuel/used exergy was defined as the exergy of the fuel consumed by the utility plant:

$$\dot{E}_f^* \equiv \dot{E}_{\text{fuel}} \text{ .} \quad (17)$$

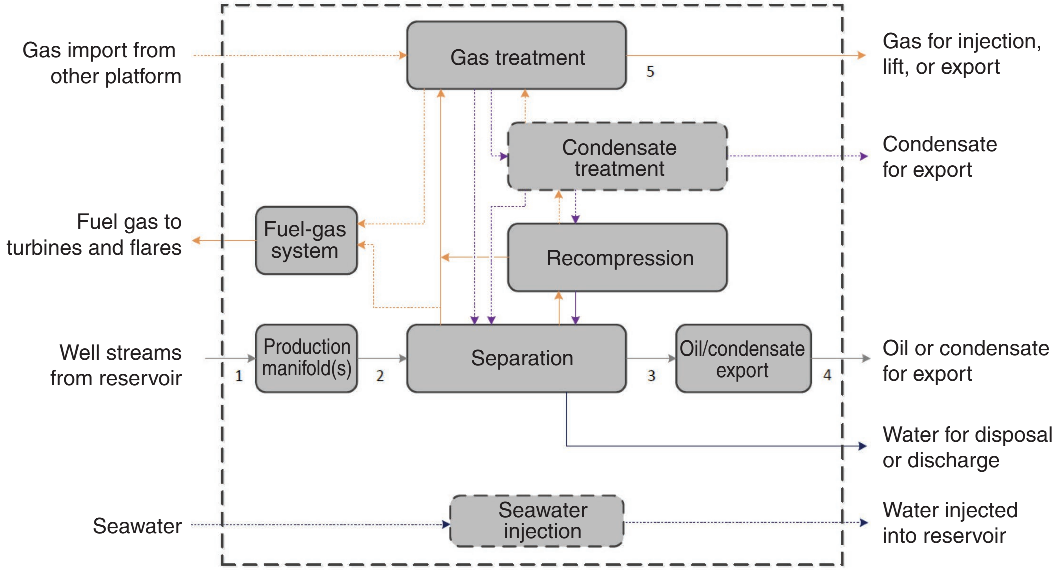

Fig. 1—A generalized overview of oil and gas processing on a North Sea platform. The arrows represent one or several mass streams, while the blocks represent different subsystems. Solid arrows are the same for all the studied platforms. Dotted arrows denote flows that are not present at all four platforms.

This gave the following formulation of the task exergy efficiency for the entire platform:

$$\varepsilon_{\text{task}*} \equiv \frac{\dot{E}_p^*}{\dot{E}_f^*} \equiv \frac{\sum_k \dot{E}_k - \dot{E}_{\text{feed}}}{\dot{E}_{\text{fuel}}} . \quad \text{(18)}$$

The same approach was used in the work of Voldsund et al. (2013a) for the oil- and gas-processing plant of a North Sea oil platform (the platform that in this work will be referred to as Platform A). Also here, the product exergy was defined as the increase in physical and chemical exergy of the feed streams:

$$\dot{E}_p \equiv \sum_k \dot{E}_k - \dot{E}_{\text{feed}} . \quad \text{(19)}$$

Because the control volume was drawn around the oil- and gas-processing plant, the fuel/used exergy was defined as the exergy associated with the thermal energy and power delivered to the process by the utility plant:

$$\dot{E}_f \equiv \dot{E}_Q^{\text{heat}} + \dot{E}_W . \quad \text{(20)}$$

The lost exergy was defined as the exergy associated with the thermal energy transferred to the cooling water:

$$\dot{E}_l \equiv \dot{E}_Q^{\text{cool}} . \quad \text{(21)}$$

This resulted in the following formulation of the task exergy efficiency:

$$\varepsilon_{\text{task}} \equiv \frac{\dot{E}_p}{\dot{E}_f} = 1 - \frac{\dot{E}_l + \dot{E}_d}{\dot{E}_f} \equiv \frac{\sum_k \dot{E}_k - \dot{E}_{\text{feed}}}{\dot{E}_Q^{\text{heat}} + \dot{E}_W} = 1 - \frac{\dot{E}_Q^{\text{cool}} + \dot{E}_d}{\dot{E}_Q^{\text{heat}} + \dot{E}_W} . \quad \text{(22)}$$

Superscript "heat" denotes thermal energy that is added to the plant for heating purposes, while superscript "cool" denotes thermal energy that leaves the plant through the cooling system. Because the focus of this work is on the oil- and gas-processing plant, Eq. 22 is used for calculating the task efficiency.

Case Studies. The four platforms investigated in this work are located in the North Sea region, and these specific platforms were selected because they present the features most common to the facilities operating in that area. Meanwhile, they differ by their age, oilfield conditions, energy demands, system, and process setups as well as by the recovery and operating strategies, and they illustrate the variety of the platforms in this area.

The purpose of all platforms is to separate oil, gas, and water and to deliver oil and gas at specified purity, pressure, and temperature levels. Conversely, there are some differences between platform types in different parts of the world. For instance, as described by Bothamley (2004), in the Gulf of Mexico, more of the oil stabilization takes place offshore and less onshore, compared with in the North Sea. This results in more-complex offshore processes, and generally a larger heating demand. The difference in heat demand can also be observed when comparing the platforms studied here with the Brazilian platform studied by De Oliveira and Van Hombeeck (1997).

An extensive description of the so-called Platform A is presented in Voldsund et al. (2013a), and all four platforms, as well as the modeling details, are described extensively in Voldsund et al. (2014). The main part of the process descriptions is repeated here to facilitate reading.

Structural Design of Oil and Gas Offshore Processing. Reservoir fluids are complex chemical mixtures that contain crude oil, gas, and water—the chemical components range from branched and aromatic hydrocarbons to various impurities such as carbon dioxide, hydrogen sulfide, and vanadium. Physical and chemical properties of such fluids vary significantly across oil fields because of different gas/oil and water/oil ratios and different reservoir conditions.

These natural differences result in different operating strategies and design setups when building these facilities. The conceptual design setup is nonetheless similar and is presented in **Fig. 1.** Production manifold, staged separation, oil/condensate pumping, gas recompression, gas treatment/compression, and fuel-gas system are typical subsystems present on an oil and gas platform.

Reservoir fluids are extracted through several oil and gas wells and enter one or several production manifolds, where the pressure is decreased and the streams are mixed before entering the separation subsystem. Oil, gas, and water phases are separated by gravity

Platform	A	B	C	D
Output streams	Exported oil	Exported condensate	Exported oil	Exported oil
	Injected gas	Exported gas	Injected gas	Exported gas
	Fuel gas	Fuel gas	Lift gas	Lift gas
	Discharged produced water	Injected produced water	Fuel gas	Fuel gas
			Discharged produced water	Discharged produced water
				Injected seawater
Product flow rates				
Oil/condensate (std m^3/h)	133	239	1106	280
Gas, 10^3 (std m^3/h)	379	763	394	63
Produced water (std m^3/h)	67	12	250	1110
Injected seawater (std m^3/h)	—	—	—	860

Table 1—Output streams and flow rates of Platforms A through D.

in two or more stages, and the pressure is further reduced by expansion in throttling valves.

Oil or condensate recovered at the outlet of the last separation stage is pumped before export by means of pipelines or shuttle tankers, while water is treated and either discharged to the environment (separate reservoir or sea) or reused for injection or lift. Gas, which consists mostly of light-weight hydrocarbons, is recompressed to a pressure equal to or greater than that at the inlet of the separation train and is processed afterward in the gas-treatment section. Depending on the export and injection specifications, gas may be dehydrated and/or compressed. In parallel, seawater may also be pumped and injected into the oil field to maintain high pressure and to recover more petroleum over time.

Main Characteristics of the Four Platforms. The four different platforms that are investigated in this paper present different characteristics. The main characteristics are listed in the following bullet points and shown in **Table 1.** The typical pressure variation through each platform process, from the wells to the export and treatment sections for oil and gas, is illustrated in **Figs. 2 and 3,** respectively.

- The first platform, denoted Platform A, has been operated for nearly 20 years and exports oil with a flow rate of 133 std m^3/h. It has a gas/oil ratio (gas and oil are given in std m^3 in the gas/oil ratio in this work) of 2800, and the gas is injected back into the reservoir to enhance oil recovery by pressure maintenance. Oil recovery is also improved by injecting water produced at another platform. Produced water is cleaned and released to the environment. The gas/oil ratio is currently increasing. The recompression train is run in off-design conditions, and anti-surge recycling is practiced to protect the compressors. The three gas-injection trains are run at full capacity.
- Platform B has been in operation for approximately 10 years and produces gas and condensate with a gas/oil ratio of 3200. Both the condensate and gas are exported, with flow rates of 239×10^3 and 761×10^3 std m^3/h, respectively. The reservoir is characterized by its high temperature and pressure, and gas and condensate are produced through pressure depletion. There is no need for further compression and dehydration after the first separation stage, resulting in a small power demand. Unlike Platform A, produced water is injected into another reservoir for disposal.
- Platform C has been in operation for approximately 10 years and is characterized by a heavy and highly viscous crude oil. There is, therefore, a significant need for heating to enhance separation between the different phases. The demand is met both with waste heat recovered from the exhaust gases of the power-generation system and by heat integration with several process streams. The gas/oil ratio is 190 and is currently increasing—gas is imported at 160×10^3 std m^3/h for injection and lift to ease oil recovery and to decrease the density of the reservoir fluid. Oil is exported with a flow rate of 1106 std m^3/h. Produced water is discharged to the sea.
- Platform D has been in operation for approximately 20 years and produces oil, gas, and condensate because the propane and medium-weight hydrocarbons content of the crude oil is significantly higher than for other crudes of this region. A par-

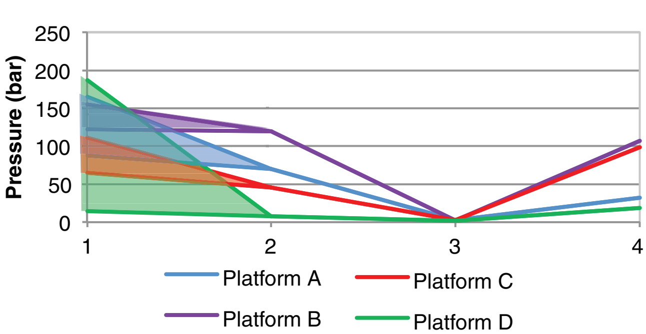

Fig. 2—Pressure profiles of oil for Platforms A, B, C, and D from well to outlet of production manifold (1→2), from outlet of production manifold to outlet of separation train (2→3), from outlet of separation train to oil export (3→4); see Fig. 1. The y-axis shows the range of pressures in the wells in operation. (Only wells producing to the high-pressure manifold are included.)

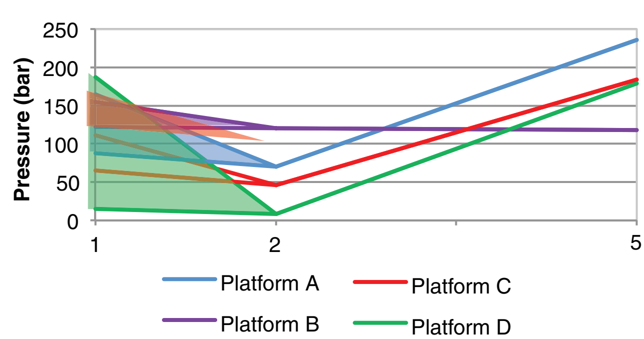

Fig. 3—Pressure profiles of gas for Platforms A, B, C, and D from well to outlet of production manifold (1→2) and from outlet of production manifold to outlet of gas treatment (2→5); see Fig. 1. The y-axis shows the range of pressures in the wells in operation. (Only wells producing to the high-pressure manifold are included.)

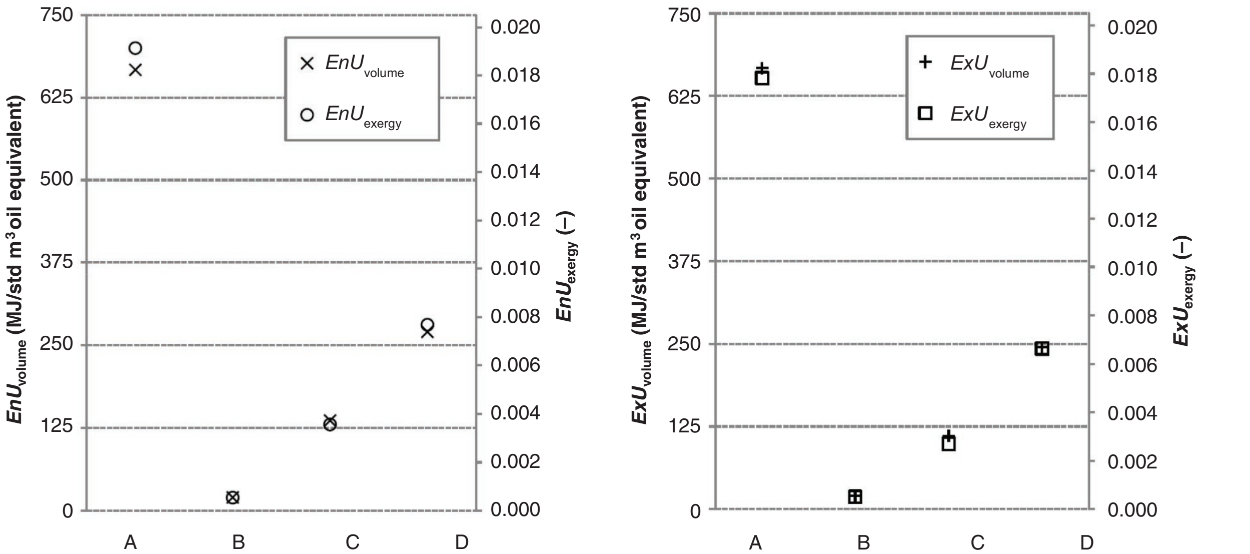

Fig. 4—Specific energy use EnU (left) and specific exergy use ExU (right) of Platforms A through D. Subscripts "volume," "energy," and "exergy" indicate whether the value is given per exported standard volume of oil equivalent, exported energy, or exported exergy, respectively.

allel condensate-treatment section was integrated to reduce the power consumption of the gas-recompression train and to allow a better separation of the different phases. The gas/oil ratio is 130, and the export flow rates of oil, condensate, and gas are 280×10^3, 6×10^3, and 6.2×10^3 std m^3/h, respectively. Gas and condensate are dehydrated, and heating is performed to ease separation of the different phases and to regenerate the glycol agent. Gas lift and water injection are used to improve oil recovery. The gas/oil ratio is currently decreasing, while the water/oil ratio is increasing. The gas- and oil-production peaks are passed, and the processing plant is at present run in conditions far from the nominal design points.

The systems were assumed at steady-state conditions, and batch processes, such as oil storage and intermittent leakages, were not considered. Process flow sheets for the processing plants of the four platforms are given in Appendix A.

The system analysis is delimited to the oil-, gas-, and water-processing plant exclusively, meaning that the utility plant (i.e., the power-generation and waste-heat-recovery modules) is not investigated. The focus of this work is on the processing plant, and inclusion of the utilities would steal the focus because large amounts of exergy are transformed or destroyed there. In the work performed by Nguyen et al. (2013), it was shown that for a complete platform, 62 to 65% of the total exergy destruction is attributable to the utility plant, while 35 to 38% is attributable to the processing plant. Most exergy destroyed in the utilities is associated with the combustion taking place in the gas turbines. Little can be done to improve this part of the process, unless power is supplied by other means. Furthermore, gas turbines operating at the design point are by far more efficient than gas turbines operating at off-design conditions. If the utility plant was included in the analyzed control volume, several of the indicators would evaluate the performance of the utility plant to a large extent and evaluate the processing plant to a lesser extent.

Results and Discussion

All the presented performance indicators were calculated for each of the four studied platforms. The two variants of specific energy use (Eqs. 8 and 9) and specific exergy use (Eqs. 11 and 12) are shown for each platform in **Fig. 4.** The calculated best-available-technologies (BAT) efficiency (Eq. 10) and the exergy efficiencies (Eqs. 15 and 22) are given in **Fig. 5. Fig. 6** shows the two types of specific exergy destruction (Eqs. 13 and 14). We discuss and compare each indicator, and evaluate them with respect to the three criteria set up in the Methodology section.

The plot on the left side of Fig. 4 shows a very large variation in the two *EnU* indicators among the platforms. Platform A has a very high specific energy use (667 MJ/std m^3 oil equivalent) because it compresses much gas (see Fig. 3 and Table 1). It is followed by Platform D, with 270 MJ/std m^3 oil equivalent; Platform C, with 136 MJ/std m^3 oil equivalent; and Platform B, with the lowest energy use at 20 MJ/std m^3 oil equivalent. For all four platforms, at least 70% of the energy use was related to the compression work; therefore, the sequence is determined by the total amount of compression work needed. The good performance of Platform B according to this indicator is explained by the high feed pressure and low gas-export pressure (Fig. 3); thus, a small compression demand.

Both *EnU* indicators give the same order of performance of platforms, but Platform A seems to perform worse when we apply

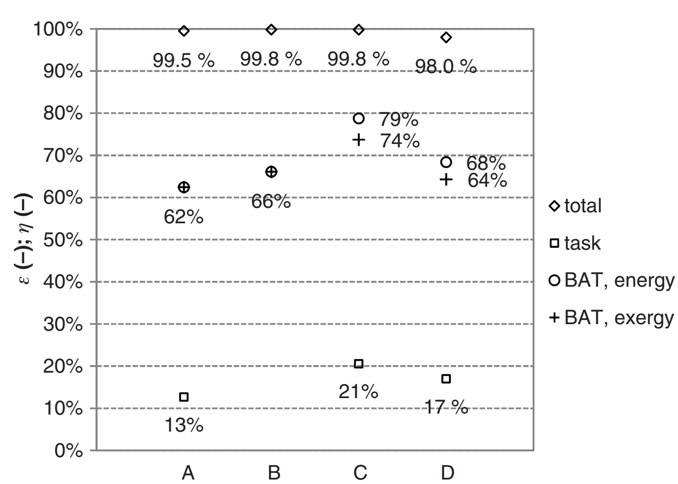

Fig. 5—Values for total and task exergy efficiency and BAT efficiency on an energy basis and an exergy basis calculated for Platforms A through D. The task exergy efficiency of Platform B is not visible in the plot, but the calculated value amounts to –215%.

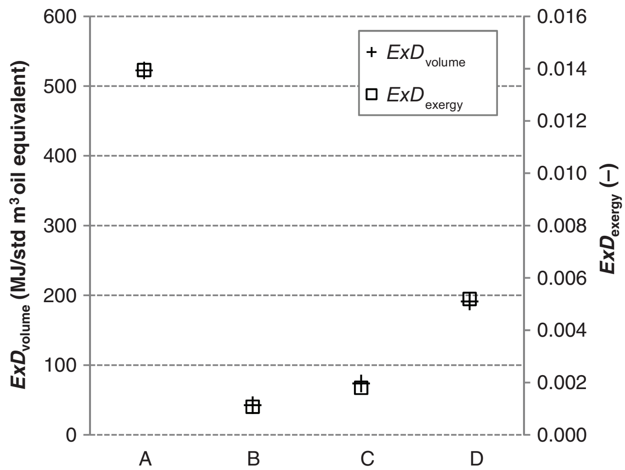

Fig. 6—Specific exergy destruction given per standard volume of oil equivalent exported and per exergy exported for Platforms A through D.

EnU_{energy} (Eq. 9) rather than EnU_{volume} (Eq. 8) for comparing the different facilities. This results from a lower energy density in the exported oil equivalents of Platform A than of the other platforms. The use of oil equivalents exported as a standard for comparison is useful from an economic point of view because oil is paid for on a volume basis. However, the ratio presented in Eq. 9 is better from a thermodynamic perspective because it takes the calorific value into account.

The plot on the right side of Fig. 4, which displays the exergy-based indicators, shows the same overall picture as the plot of the energy-based indicators (left side of Fig. 4). With the exergy-based indicators, the energy is evaluated in terms of theoretical ability to perform work. In this approach, heat is valued lower than power, and heat with higher temperature is valued higher than heat with temperature closer to the ambient. The reason that the indicators give such similar results is that very little, if any, heat is used on these platforms. This also results in similar values for the two types of indicators. For Platforms A and B, $ExU_{volume}=EnU_{volume}$ because no heat is added to the processes on these platforms. By closer inspection of the indicators of Platforms C and D, we see that $ExU_{volume}<EnU_{volume}$. These two platforms require some heat, and the exergy transported with heat is smaller than its associated thermal energy. Platforms with $ExU \approx EnU$ are typical for the North Sea area because of the low heat demand. In other parts of the world, larger quantities of heat may be required. One example is the Brazilian platform studied by De Oliveira and Van Hombeeck (1997), where the petroleum enters the separation subsystem at a much lower temperature, and large quantities of heat are used to preheat the feeds for enhancing the oil, gas, and water separation. For a comparison of oil and gas platforms worldwide, the use of ExU instead of EnU would therefore make a difference.

In general, an exergy-based evaluation of performance is preferred to an energy-based evaluation. In energy analysis, all types of energy inputs or outputs are taken as equal, while in exergy analysis, the inputs and outputs are measured in terms of the potential to do work (Kotas 1995). For the specific examples provided here, specific exergy use instead of specific energy use as a measure of performance motivates the use of low-temperature heat for heating instead of high-temperature heat or power that could have been used for other purposes.

The specific energy use EnU and the specific exergy use ExU do not indicate the technically achievable or theoretically achievable improvement potential. In this respect, they do not fulfil Criteria 1 and 2, but they do illustrate the total amount of energy resources used to extract the petroleum, and therefore satisfy Criterion 3.

From Fig. 5, we first note that the total exergy efficiencies of all platforms are very high. All platforms have a performance within 98.0 to 99.8%, as measured with this indicator alone. This is because the exergy content of hydrocarbons passing through the system is very high. Such high total exergy efficiencies are expected for all offshore platforms. The property is characteristic for facilities processing oil and gas; see Margarone et al (2011), Nguyen et al. (2013), or Rivero et al. (2004) for other examples. The total exergy efficiency alone may give the wrong impression that there is limited room for improvement or that no improvement is needed. Kotas (1995) and Tsatsaronis (2007) support this view, arguing that the concept of total exergy efficiency may be directly misleading. This type of efficiency has little sensitivity to performance improvements, and may therefore hide the potential to reduce system inefficiencies and mask improvement strategies. Thus, the total exergy efficiency does not meet any of the three presented criteria.

The task exergy efficiency, as formulated in Eq. 22, ranges between 13 and 21% for Platforms A, C, and D (see Fig. 5). However, for Platform B, the calculated value amounts to −215%. The negative value for Platform B is because of decreasing pressure between the inlet and outlet streams (refer to Figs. 2 and 3). The task of this platform is different from that of the Brazilian case in which this formulation was first used. In the Brazilian case, the tasks include separation, compression, and pumping. The feed pressure was 11 bar, while the produced-gas and -oil pressures were 174 and 69 bar, respectively. For Platform B, the feed streams have high pressures (122–125 bar), and the pressures required for the produced oil and gas are lower and are reached by throttling. The tasks for Platform B are separation and expansion.

Exergy increase because of separation is less than 200 kW in any case, and is less than the amount of exergy destroyed by throttling. On Platform B, power and physical exergy are used to achieve this small chemical exergy increase and to achieve product streams with lower physical exergy than the feed streams. Thus, it is correct that Platform B has a lower performance when compared with the theoretically achievable potential, even though the use of Eq. 22 may be misleading.

For Platforms A and C, the tasks are nearly the same as for the Brazilian case. On Platform A, the required oil-export pressure is lower than the feed-stream pressures, while the required gas-injection pressure is higher. The task of this platform is, therefore, mainly to perform separation and compression work, but not much pumping. However, the gas/oil ratio is high and the produced gas dominates the “product” of the task efficiency. On Platform C, the oil-export pressure is higher than most of the feed streams, and the gas-injection pressure is higher than all feed streams. Eq. 22 may therefore be used as an approximation for these two cases.

On Platform D, the oil-export pressure is lower, while the gas-injection pressure is higher than the pressure of most feed streams. Therefore, the task of the platform is separation and compression, but not so much pumping. The gas/oil ratio is lower than, for instance, that on Platform A. The task efficiency as formulated in Eq. 22 is therefore less suitable for this platform.

In addition, Platform D has high water content in the feed (see Table 1) and discharges a significant amount of water to the sea. The water-discharge streams on all platforms are waste streams, and the exergy content of these streams is, in practice, lost exergy. In Eq. 22, the water is counted as a desired product. The water-flow rates on Platforms A through C are smaller than on Platform D, and thus have lower impact on the resulting efficiency. However, for Platform D, the high water-flow rate will impact the calculated efficiency formulated in Eq. 22.

The task efficiency, as formulated in Eq. 22, measures the use of the theoretical potential for Platforms A and C. Performance losses in all types of processes, including throttling, compression, pumping, and heat transfer, are taken into account. However, because the tasks differ from one platform to another, and because no

Performance Indicator	Criterion 1	Criterion 2	Criterion 3
EnU	No	No	Yes
ExU	No	No	Yes
$\varepsilon_{\mathrm{total}}$	No	No	No
$\varepsilon_{\mathrm{task}}$	No	Yes, but…	No
η_{BAT}	Yes, but…	No	No
ExD	No	No	Yes

Table 2—Overview of performance indicators and their fulfilment of the criteria for good indicators.

distinction was made between product streams and waste streams, this formulation did not provide a realistic evaluation for all four platforms considered. It should be further developed to be suitable for evaluating several, and different, types of offshore platforms. Thus, Criterion 2 is partly fulfilled. The formulation in Eq. 22 does not evaluate whether the practical achievable potential is used or the total use of energy resources, so Criteria 1 and 3 are not fulfilled.

The BAT efficiency is defined to show the potential for improvement by updating old process units. These efficiencies for our platforms range from 62 to 79% on an energy basis and from 62 to 74% on an exergy basis (see Fig. 5). This implies that the energy and exergy demands could be reduced to these percentages if state-of-the-art compressors and pumps were integrated to replace the current ones. As emphasized in the discussion on the specific energy use and the specific exergy use, exergy-based indicators are preferred to energy-based indicators.

It may be expected that old platforms have a lower BAT efficiency than newer platforms. The technologies available on the market are being improved continuously, and old processes become less efficient with time, as a result of aging and operation under off-design conditions. This is the case for our four platforms, and the consequences of aging and off-design conditions are possibly seen. Platforms B and C, which have been in operation for approximately 10 years less than Platforms A and D, seem to perform slightly better.

The gas-treatment facility studied by Margarone et al. (2011) consumed twice as much power as an improved layout with state-of-the-art technologies. Svalheim and King (2003) argued that the oil and gas facilities they studied had an excellent energy performance and a small improvement potential. The four platforms studied here seem to lie between these two scenarios. They have a similar or better performance with the BAT efficiency than the facility studied by Margarone et al. (2011), but all of them show a considerable improvement potential.

A limitation with the BAT efficiency is that it depends on the interpretation of BAT. For instance, the state-of-the-art compressor efficiencies differ for the type of fluid processed, the component subclass (e.g., centrifugal, axial, reciprocating), and the pressure ratio, while efficiencies of pumps depend on, among other characteristics, the magnitude and specific speed of the fluid volume flow. In this work, all actual compressors and pumps were replaced by components with an adiabatic efficiency of 85%, while in reality, the state-of-the-art efficiency varies slightly between the components. Replacement of heat exchangers and throttling valves with more-effective equipment and expanders, if possible, was not considered. Moreover, the BAT efficiencies cannot show any improvement potential for systems for which there is no mature technology readily available on the market. This is the case for production manifolds—depressurization is achieved by valve throttling, and multiphase expansion of fluids containing sand, water, oil, and gas is not currently feasible. Defining the state-of-the-art performance for mature technologies is also an issue because they evolve with time and may be improved in the future. In addition, the indicator compares a specific platform design with the same design using state-of-the-art technologies. The improvement potential associated with changes and improvements of the process setup is thereby not taken into account.

We conclude that the BAT efficiencies enable us to evaluate the potential for improving the platforms with the technologies already present on the market, and therefore they satisfy Criterion 1. However, they can be used neither for assessing the performance of a facility in relation to its theoretically achievable performance, nor for estimating the total use of energy resources. Criteria 2 and 3 are, therefore, not fulfilled.

The last indicators studied in this work, the specific exergy destruction per oil equivalent exported or per exergy exported (Eqs. 13 and 14) are shown in Fig. 6. The *ExD* indicators give, according to their definition, a direct measure of the exergy destroyed. This is an essential difference compared with the *ExU* indicators, because some of the consumed exergy is transformed into another form and exported as part of the product. Platform A seems to perform the worst, with *ExD* of 523 MJ/std m^3 oil equivalent, and Platform D follows with 192 MJ/std m^3 oil equivalent. Platforms B and C have nearly the same specific exergy destruction, with 43 and 74 MJ/std m^3 oil equivalent, respectively. The same conclusions drawn in Fig. 4 can be drawn here. It makes little difference whether this indicator is used on an oil- or exergy-equivalent basis, but we suggest the use of exergy equivalents for the same reasons discussed previously. Platforms A and D perform slightly worse with the latter measure, reflecting that these platforms have the lowest exergy density in the exported oil equivalents. The *ExD* indicators and the *ExU* indicators, as shown in Fig. 4, follow the same trends. This is expected because more work is performed and more entropy is produced as a consequence. An exception to this rule is Platform B, which performs slightly worse compared with the other platforms. Exergy entering the process with the feed streams is destroyed, and this is not accounted for in the *ExU* indicator at the difference of the *ExD* indicator.

The *ExD* indicators do not evaluate the use of technically achievable potential, so Criterion 1 is not fulfilled. If all included processes had been reversible, the values for the *ExD* indicators would be zero, and in this respect, the indicator would evaluate the use of the theoretical potential. However, as mentioned previously, it favors processes in which only a small amount of work is needed. It is therefore particularly sensitive to the field and export conditions, and Criterion 2 is not fulfilled. The indicators evaluate the total use of resources, so Criterion 3 is fulfilled.

The results from the preceding reasoning are summarized in **Table 2.** Criterion 1 (to evaluate the use of the technically achievable potential) is fulfilled only by the BAT efficiency, but this efficiency presents some limitations. Criterion 2 (to evaluate the use of the theoretically achievable potential) is fulfilled partly by the task exergy efficiency found in literature for the Brazilian oil platform. Criterion 3 (to evaluate the total use of energy resources) is fulfilled by the *EnU, ExU,* and *ExD* indicators. None of the indicators fulfilled more than one of the criteria.

The concept of the BAT efficiency could be improved by considering state-of-the-art performance of all types of process units. When exergy-based, this is similar to the approach of Tsatsaronis and Park (2002), which distinguishes between avoidable and unavoidable exergy destruction. The BAT efficiency could be further developed by also considering possible improvements in process setup.

The *EnU*, *ExU,* and *ExD* indicators fulfilled Criterion 3. As discussed previously, the *ExU* indicator is preferred to the *EnU* indicator because, with the *ExU* indicator, the different qualities of power, high-temperature thermal energy, and low-temperature thermal energy are taken into account. Further, the *ExD* indicator presents some benefits compared with the *ExU* indicator because it does not punish installations for the part of the consumed exergy that they export, while it does punish destruction of exergy provided through the feed streams. The use of the *ExD* indicator is in accordance with Kjelstrup et al. (2010), who proposed that all companies should report their exergy destruction or entropy production.

The *ExD* indicator can be developed further by applying the concept of avoidable/unavoidable exergy destruction presented by Tsatsaronis and Park (2002), or the concept of minimum entropy production presented by Johannessen et al. (2002), Johannessen and Røsjorde (2007), and Wilhelmsen et al. (2010). In the concept of minimum entropy production, a fixed production target and other practical constraints are set for a process, and an optimization is performed to find a value for the minimum entropy production with the set constraints. These two approaches provide an alternative benchmark to the reversible process. The *ExD* indicator could, with these approaches, fulfil Criterion 1 in addition to Criterion 3 because it would evaluate the use of the technically achievable potential; it would be zero if none of the technically achievable potential was wasted.

The performance indicators recommended in the present work illustrate different aspects of a platform performance and will vary over time. Newer platforms will, in general, perform better than older ones because these platforms operate closer to their design conditions, the equipment is newer, and because the amount of exported exergy is high. Information on performance in the different phases of the life of an oil and gas facility could be helpful for decision makers in making trade-offs between exergy costs of operation vs. investment costs of new apparatus. They could also ease a comparison with different technologies, such as extraction of petroleum from tar sand. The indicators are also useful for evaluation of platforms in other parts of the world. The main differences in the results are expected to be of higher importance to the heating operations.

Because the scope of this work was to evaluate thermodynamic performance parameters, environmental parameters were not considered within this work. Emissions of carbon dioxide (CO_2) from an oil and gas platform are, to a major extent, caused by the on-site fuel consumption in diesel and gas turbines to meet the power and heat demands of the processing plant (Statistics Norway 2013). The energy and the exergy of the power and heat demands make up the numerator in the *EnU* and *ExU* indicators. The widely used environmental indicator (namely, the specific CO_2 emissions per unit of produced petroleum) is therefore directly related to *EnU* and *ExU,* as long as the heat and power are produced on on-site utility systems and unless CO_2 capture is integrated on the platform. Furthermore, the amount of destroyed exergy gives rise to fuel use that could have been avoided. The CO_2 emissions are therefore indirectly related to the *ExD* indicator. The BAT efficiency and the task exergy efficiency both motivate optimal energy management, and also trigger CO_2-emission reductions.

The criteria chosen for evaluation of the indicators focus on the thermodynamic aspects of the indicators. Some may argue that a useful indicator would be one that can be applied easily in practice, with a limited amount of resources and time, and understood by all public types. The results of the present work may be generalized to other processing plants involving significant amounts of transit exergy. This may be other petrochemical facilities (e.g., liquefied-natural-gas-production plants).

Conclusion and Perspectives

In this paper, four North Sea oil and gas platforms were compared by use of several different energy- and exergy-based performance indicators. The list of indicators used is not exhaustive because other parameters illustrating the performance of oil and gas facilities have also been used (see Rivero 2002). However, we believe that the most central parameters have been covered. Three criteria were listed for a well-performing indicator, and we conclude with the following recommendations:

- None of the studied indicators fulfilled all criteria alone; thus, a set of different indicators is needed for a thorough evaluation of thermodynamic performance of oil and gas platforms.
- For an evaluation of oil and gas platforms worldwide, we conclude that exergy-based indicators are better than energy-based indicators.
- The best-available-technologies (BAT) indicator evaluates the use of technically achievable potential.
- The concept of task exergy efficiency evaluates the use of theoretical potential. The formulation studied here provides a realistic evaluation for platforms with higher physical exergy in the output streams than in the input streams. Further work should be conducted to find a formulation for task exergy efficiency suitable for all platforms.
- The specific exergy destruction *ExD* evaluates the total use of resources by the installations. This indicator quantifies the use of the theoretical potential of the process.
- We recommend use of the BAT efficiency on an exergy basis, and the use of task exergy efficiency and the specific exergy destruction when evaluating the thermodynamic performance of offshore oil and gas processing.
- We support the reasoning of Tsatsaronis and Park (2002) and propose to further develop an indicator tailored for offshore use by including in a better manner unavoidable and avoidable exergy losses in the process.

Nomenclature

e = specific exergy, kJ/kg
e^{ch} = specific chemical exergy, kJ/kg
e^{kin} = kinetic component of specific exergy, kJ/kg
e^{ph} = specific physical exergy, kJ/kg
e^{pot} = potential component of specific exergy, kJ/kg
$\bar{e}_i$ = chemical exergy of pure component i, kJ/kg
$\bar{\bar{e}}_i$ = specific chemical exergy of component i in mixture, kJ/kg
e_j = specific exergy in stream j, kJ/kg
$\dot{E}_d$ = exergy-destruction rate, kW
$\dot{E}_{export}$ = exergy-export flow rate, kW
$\dot{E}_f$ = used/fuel exergy flow rate, kW
$\dot{E}_f^*$ = used/fuel exergy flow rate for overall platform, kW
$\dot{E}_{feed}$ = exergy flow rate of all feed streams, kW
$\dot{E}_{fuel}$ = exergy flow rate of fuel consumed, kW
$\dot{E}_{in}$ = input exergy flow rate, kW
$\dot{E}_k$ = exergy flow rate of product stream k, kW
$\dot{E}_l$ = exergy-loss flow rate, kW
$\dot{E}_{out}$ = output exergy flow rate, kW
$\dot{E}_{out,l}$ = lost output exergy flow rate, kW
$\dot{E}_{out,u}$ = useful output exergy flow rate, kW
$\dot{E}_p$ = exergetic product flow rate, kW
$\dot{E}_p^*$ = exergetic product flow rate for overall platform, kW
$\dot{E}_Q$ = heat exergy flow rate, kW
$\dot{E}_Q^{cool}$ = exergy flow rate leaving with cooling water, kW
$\dot{E}_Q^{heat}$ = exergy flow rate added for heating, kW
$\dot{E}_{Q,in}$ = input heat exergy flow rate, kW
$\dot{E}_W$ = work exergy flow rate, kW
$\dot{E}_{W,in}$ = input work exergy flow rate, kW
EnU_{energy} = specific energy use, given per energy (LHV) exported, –
EnU_{volume} = specific energy use, given per exported volume, kJ/std m^3

ExD_{exergy} = specific exergy destruction, given per exergy exported, –
ExD_{volume} = specific exergy destruction, given per exported volume, kJ/std m^3
ExU_{exergy} = specific exergy use, given per exergy exported, –
ExU_{volume} = specific exergy use, given per exported volume, kJ/std m^3
h = mass enthalpy, kJ/kg
$h_{i,0}$ = mass enthalpy of pure component i at T_0 and p_0, kJ/kg
h_0 = mass enthalpy at T_0 and p_0, kJ/kg
LHV = lower heating value, kJ/kg
$\dot{LHV}_{\text{export}}$ = energy (LHV) export flow rate, kW
$\dot{m}_j$ = mass-flow rate in stream j, kg/s
p_0 = ambient pressure, Pa
$\dot{Q}$ = heat, kW
$\dot{Q}_{\text{BAT,in}}$ = input heat with BAT, kW
$\dot{Q}_{in}$ = input heat flow rate, kW
s = mass entropy, kJ/kg·K
$s_{i,0}$ = mass entropy of pure component i at T_0 and p_0, kJ/kg·K
s_0 = mass entropy at T_0 and p_0, kJ/kg·K
T_j = temparture at system boundary, K
T_0 = ambient temperature, K
$\dot{V}_{\text{export}}$ = volume export flow rate, std m^3/s
$\dot{W}$ = work, kW
$\dot{W}_{\text{BAT,in}}$ = input work with BAT, kW
$\dot{W}_{\text{in}}$ = input work flow rate, kW
x_i = mass fraction of component i, –
$\varepsilon_{\text{task}}$ = task exergy efficiency, –
$\varepsilon_{\text{task*}}$ = task exergy efficiency for overall platform, –
$\varepsilon_{\text{total}}$ = total exergy efficiency, –
η_{BAT} = BAT efficiency, –

Acknowledgments

The motivation from Statoil's new-idea project of reducing carbon dioxide emissions from offshore oil and gas platforms is essential to this study. The Faculty of Natural Sciences and Technology at the Norwegian University of Science and Technology is acknowledged for financial support by the first author. The second author acknowledges the funding from the Norwegian Research Council through the Petromaks program, within the project 2034/E30 led by Teknova.

References

Bejan, A., Tsatsaronis, G., and Moran, M. 1996. *Thermal Design & Optimization*. New York: John Wiley & Sons.

Bothamley, M. 2004. Offshore Processing Options for Oil Platforms. Presented at the SPE Annual Technical Conference and Exhibition, Houston, 26–29 September. SPE-90325-MS. http://dx.doi.org/10.2118/90325-MS.

De Oliveira Jr., S. and Van Hombeeck, M. 1997. Exergy analysis of petroleum separation processes in offshore platforms. *Energy Conversion and Management* **38** (15–17): 1577–1584. http://dx.doi.org/10.1016/S0196-8904(96)00219-1.

Fratzscher, W., Brodjanskij, V.M., Michalek, K. 1986. *Exergie: Theorie und Anwendung*. Leipzig, Germany: Deutscher Verlag für Grundstoffindustrie.

Johannessen, E. and Røsjorde, A. 2007. Equipartition of entropy production as an approximation to the state of minimum entropy production in diabatic distillation. *Energy* **32** (4): 467–473. http://dx.doi.org/10.1016/j.energy.2006.06.009.

Johannessen, E., Nummedal, L. and Kjelstrup, S. 2002. Minimizing the entropy production in heat exchange. *International Journal of Heat and Mass Transfer* **45** (13): 2649–2654. http://dx.doi.org/10.1016/S0017-9310(01)00362-3.

Kjelstrup, S., Bedeaux, D., Johannessen, E. et al. 2010. *Non-Equilibrium Thermodynamics for Engineers*. Singapore: World Scientific Publishing Co.

Kotas, T.J. 1995. *The Exergy Method of Thermal Plant Analysis*. Malabar: Krieger Publishing.

Lior, N. and Zhang, N. 2007. Energy, exergy, and Second Law performance criteria. *Energy* **32** (4): 281–296. http://dx.doi.org/10.1016/j.energy.2006.01.019.

Margarone, M., Magi, S., Gorla, G. et al. 2011. Revamping, Energy Efficiency, and Exergy Analysis of an Existing Upstream Gas Treatment Facility. *J. Energy Resour. Technol.* **133** (1): 012001. http://dx.doi.org/10.1115/1.4003627.

Moran, M.J. 1989. *Availability Analysis: A Guide to Efficient Energy Use*, second edition. New York: ASME Press.

Nguyen, T.-V., Pierobon, L., Elmegaard, B. et al. 2013. Exergetic assessment of energy systems on North Sea oil and gas platforms. *Energy* **62**: 23–36. http://dx.doi.org/10.1016/j.energy.2013.03.011.

Rivero, R. 2002. Application of the exergy concept in the petroleum refining and petrochemical industry. *Energy Conversion and Management* **43** (9–12): 1199–1220. http://dx.doi.org/10.1016/S0196-8904(02)00008-0.

Rivero, R., Rendón, C., and Gallegos, S. 2004. Exergy and exergoeconomic analysis of a crude oil combined distillation unit. *Energy* **29** (12–15): 1909–1927. http://dx.doi.org/10.1016/j.energy.2004.03.094.

Statistics Norway. 2013. Emissions of greenhouse gases: Create your own tables and graphs, http://www.ssb.no/emner/01/04/10/klimagassn/ (accessed October 2013).

Svalheim, S.M. and King, D.C. 2003. Life of Field Energy Performance. Presented at Offshore Europe, Aberdeen, 2–5 September. SPE-83993-MS. http://dx.doi.org/10.2118/83993-MS.

Tsatsaronis, G. and Park, M.-H. 2002. On avoidable and unavoidable exergy destructions and investment costs in thermal systems. *Energy Conversion and Management* **43** (9–12): 1259–1270. http://dx.doi.org/10.1016/S0196-8904(02)00012-2.

Tsatsaronis, G. 2007. Definitions and nomenclature in exergy analysis and exergoeconomics. *Energy* **32** (4): 249–253. http://dx.doi.org/10.1016/j.energy.2006.07.002.

Voldsund, M., Nguyen, T.V., Elmegaard, B. et al. 2013b. Performance indicators for evaluation of North Sea oil and gas platforms. In *Proceedings of ECOS 2013 – The 26th International Conference on Efficiency, Cost, Optimization and Environmental Impact of Energy Systems, 16–19 July 2013, Guilin, China*, ed. H. Jin and N. Lior, Chinese Society of Engineering Thermophysics.

Voldsund, M., Nguyen, T.V., Elmegaard, B. et al. 2014. Exergy destruction and losses on four North Sea offshore platforms: A comparative study of the oil and gas processing plants. *Energy* **74**: 45–58. http://dx.doi.org/10.1016/j.energy.2014.02.080.

Voldsund, M., Ertesvåg, I.S., He, W. et al. 2013a. Exergy analysis of the oil and gas processing on a North Sea oil platform on a real production day. *Energy* **55**: 716–727. http://dx.doi.org/10.1016/j.energy.2013.02.038.

Wall, G. 2004. Exergy. In *Encyclopedia of Energy*, 593–606, Academic Press. http://dx.doi.org/10.1016/B0-12-176480-X/00126-1.

Wilhelmsen, Ø., Johannessen, E., and Kjelstrup, S. 2010. Energy efficient reactor design simplified by second law analysis. *International Journal of Hydrogen Energy* **35** (24): 13219–13231. http://dx.doi.org/10.1016/j.ijhydene.2010.08.118.

Appendix A

This appendix contains process flow sheets for the four platforms given in **Figs. A-1 through A-4.** Details on process data for the platforms are described by Voldsund et al. (2013a; 2014).

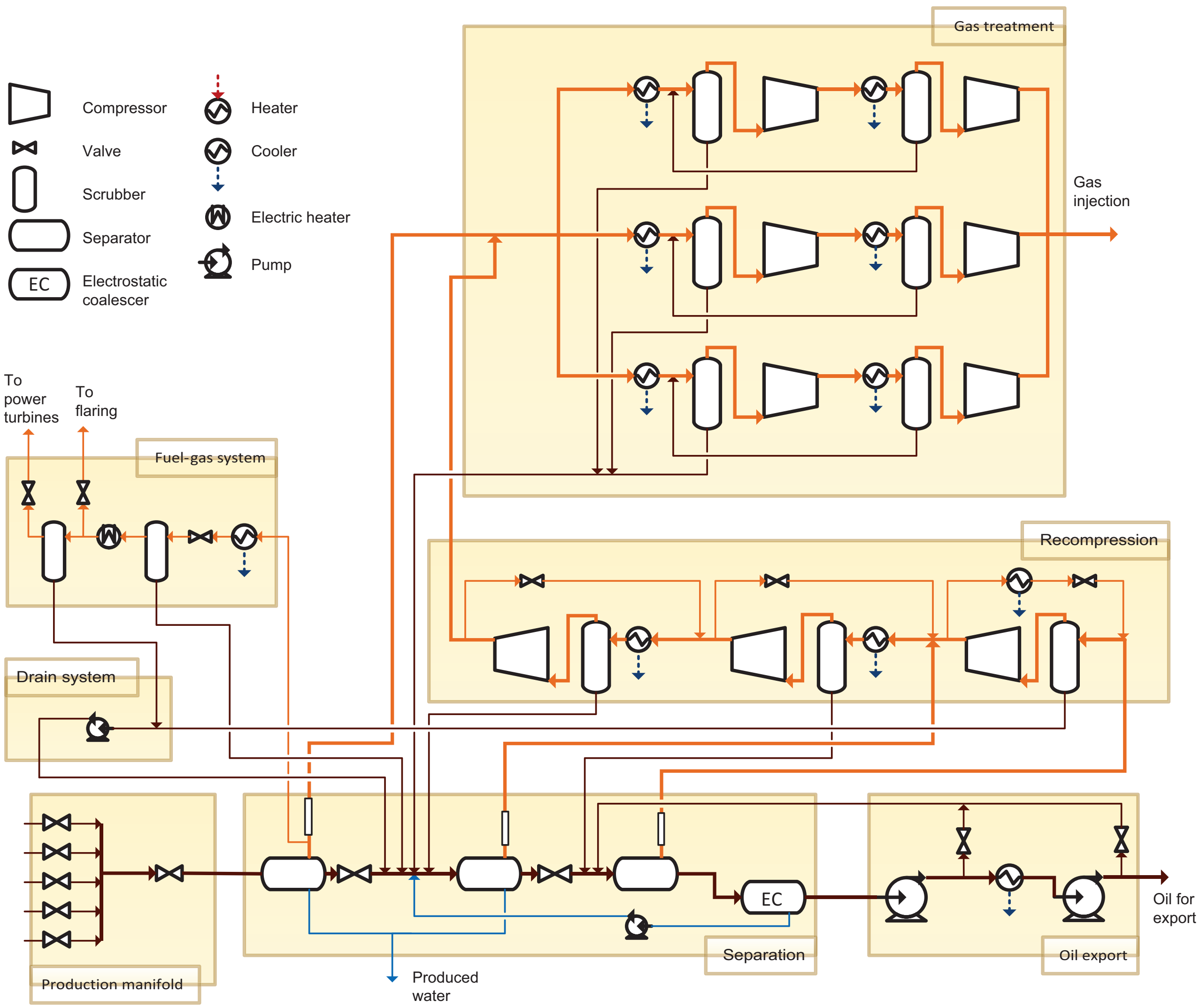

Fig. A-1—Process flow sheet of Platform A. Gas streams are shown with orange arrows; water streams are shown with blue arrows; and oil, condensate, and mixed streams are shown with brown arrows.

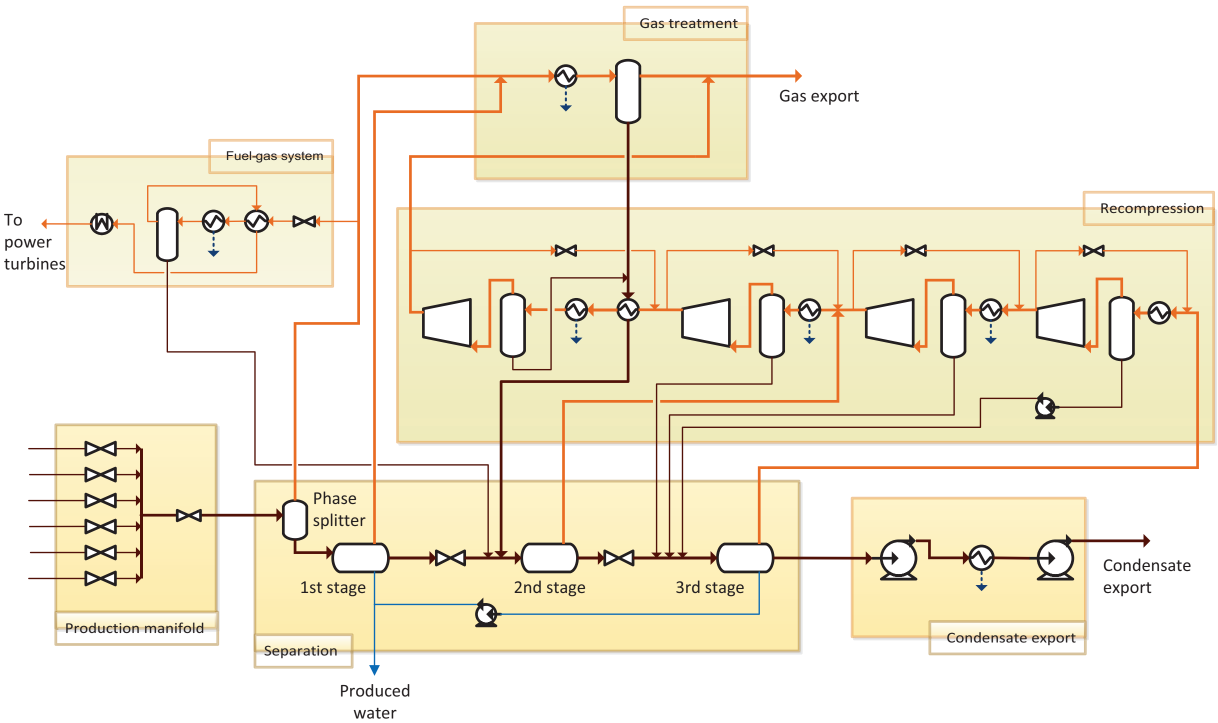

Fig. A-2—Process flow sheet of Platform B. Gas streams are shown with orange arrows; water streams are shown with blue arrows; and oil, condensate, and mixed streams are shown with brown arrows. Symbol explanations can be found in Fig. A-1.

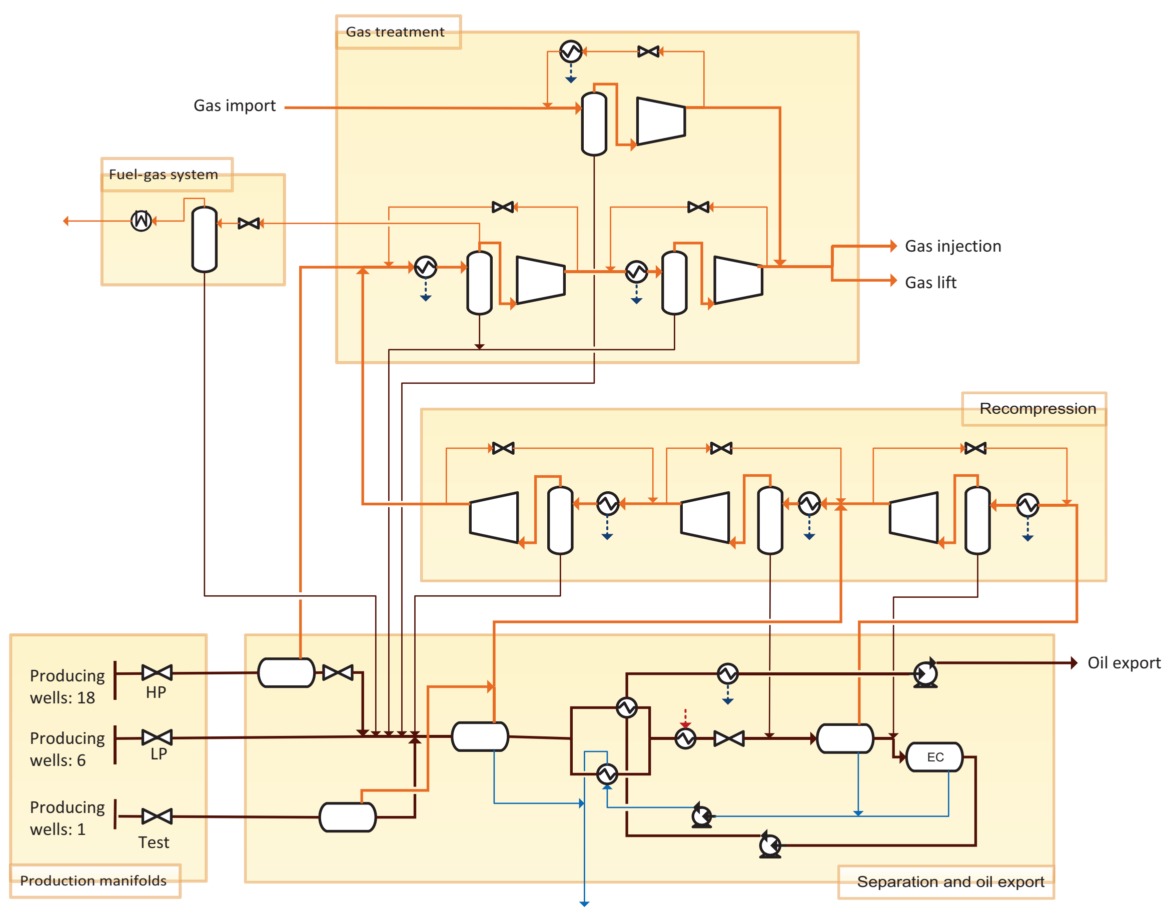

Fig. A-3—Process flow sheet of Platform C. Gas streams are shown with orange arrows; water streams are shown with blue arrows; and oil, condensate, and mixed streams are shown with brown arrows. Symbol explanations can be found in Fig. A-1.

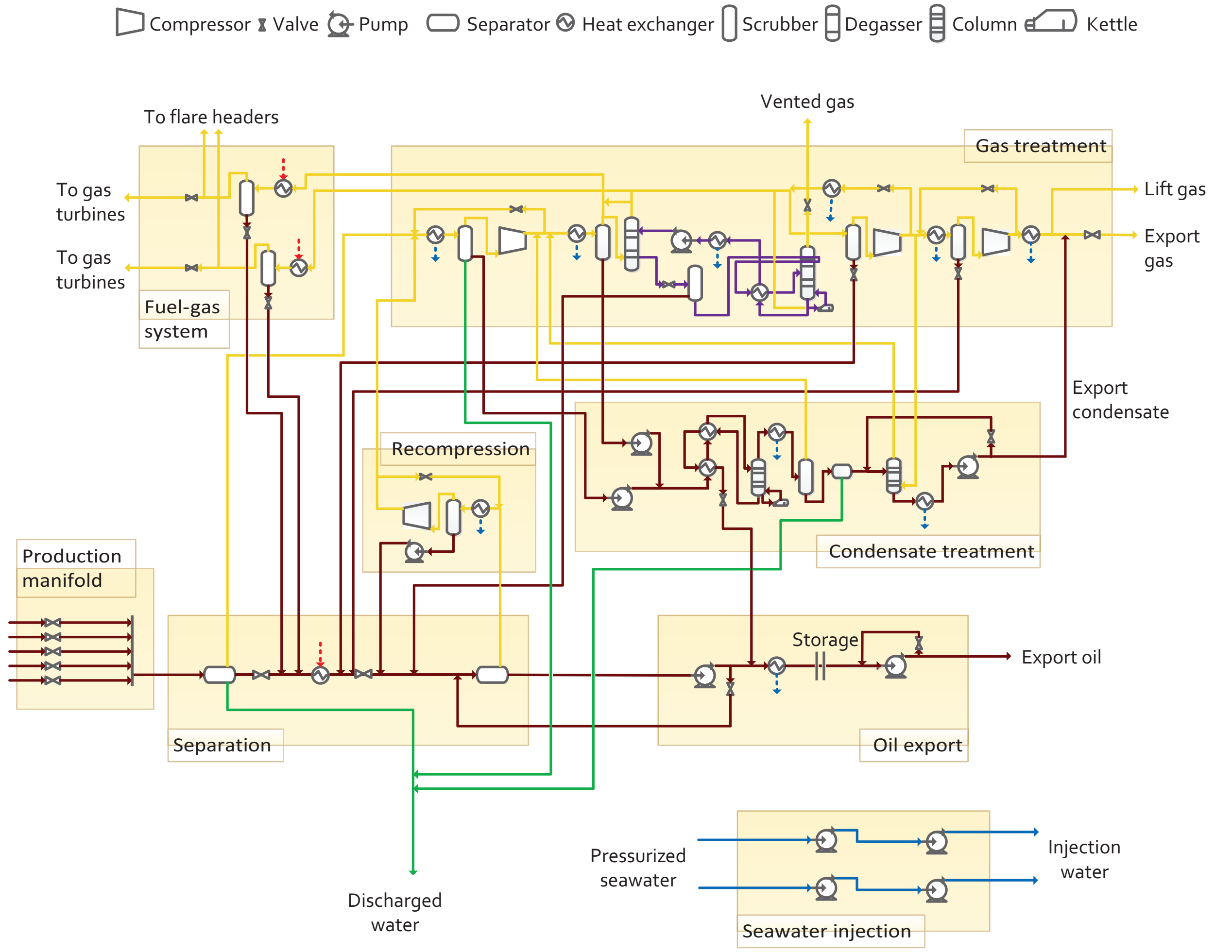

Fig. A-4—Process flow sheet of Platform D. Gas streams are shown with orange arrows; water streams are shown with blue arrows; glycol is shown with purple arrows; and oil, condensate, and mixed streams are shown with brown arrows.

Mari Voldsund is a PhD degree candidate at the Norwegian University of Science and Technology. Her main area of research is exergy analysis of offshore oil and gas processing. She holds a master's degree in physical chemistry, also from the Norwegian University of Science and Technology.

Tuong-Van Nguyen is a PhD degree candidate at the Technical University of Denmark, Kongens Lyngby. His main area of research is within design, modeling, and optimization of oil and gas platforms. Nguyen holds a master's degree in sustainable energy systems from Chalmers University of Technology, Göteborg, Sweden, and an engineer's degree in process engineering from École des Mines d'Albi-Carmaux, Albi, France.

Brian Elmegaard is an associate professor and head of the Thermal Energy Section at the Technical University of Denmark. His research focuses on analysis and optimization of thermal systems on the basis of numerical simulation and advanced thermodynamic methods (e.g., exergy analysis). Elmegaard's work includes refrigeration and heat pumps, combined heat and power, electricity storage, biomass systems, and thermal power.

Ivar S. Ertesvåg is a professor of engineering thermodynamics at the Department of Energy and Process Engineering, Norwegian University of Science and Technology. His research interests include exergy analysis of thermochemical processes, second-law analysis of turbulent reacting flows, and modeling of turbulent combustion and other turbulent flows. Ertesvåg was a board member of the Scandinavian-Nordic Section of the Combustion Institute from 2004 to 2011, and he has written a textbook on turbulent flow and combustion.

Signe Kjelstrup has been a professor of physical chemistry since 1985 at the Norwegian University of Science and Technology. Since 2005, she has been a part-time chair on irreversible thermodynamics and sustainable processes at the Technical University of Delft, The Netherlands. Kjelstrup's work in nonequilibrium thermodynamics concerns electrochemical cells, membrane systems, and entropy-production minimization in process equipment. She authored the book *Non-Equilibrium Thermodynamics for Engineers*, in addition to several other books in the area of nonequilibrium thermodynamics.