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On the definition of exergy efficiencies for petroleum systems: Application to offshore oil and gas processing

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Abstract

Exergy-based efficiencies are measures of the thermodynamic perfection of systems and processes. A meaningful formulation of these performance criteria for petroleum systems is difficult because of (i) the high chemical exergy of hydrocarbons, (ii) the large variety of chemical components, and (iii) the differences in operating conditions between facilities. This work focuses on offshore processing plants, considering four oil platforms that differ by their working conditions and designs. Several approaches from the scientific literature for similar processes are presented and applied to the four cases. They showed a low sensitivity to performance improvements, gave inconsistent results, or favoured facilities operating under certain conditions. We suggest an alternative formulation, called the *component-by-component* exergy efficiency, which builds on the decomposition of the exergy flows at the level of the chemical compounds. It allows therefore for sound comparisons of separation systems, while it successfully evaluates their theoretical improvement potentials. The platform displaying the lowest efficiency (1.7 %) is characterised by little pumping and compression works, at the opposite of the one displaying the highest performance (29.6 %). A more realistic measure of the technical potential for improving these systems can be carried out by splitting further the exergy destruction into its avoidable and unavoidable parts.

Keywords: Exergy, Efficiency, Petroleum, Oil and gas platforms

1. Introduction

Conventional indicators for evaluating the performance of oil and gas platforms, such as the specific power consumption, the specific CO_2 emissions, or the energy efficiency, present inherent limitations. They provide useful information on the energy use of the on-site processes, but they cannot be used alone to compare the performance of different facilities [1,2]. The specific power consumption is defined as the power consumed per oil equivalent exported, the specific CO_2 emissions as the amount of carbon dioxide emitted per unit of oil equivalent exported, and the energy efficiency as the ratio of the energy exported with the oil and gas sent onshore to the energy entering the system with the feed streams. Each oil field has different natural characteristics (e.g. gas-to-oil ratio, well-fluid composition, field size) and comparing different facilities with these metrics is therefore misleading.

The exergy analysis method is a quantitative assessment tool that is based on both the 1st and 2nd Laws of Thermodynamics. This thermodynamic method presents advantages over a conventional energy analysis,

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Nomenclature

T	Temperature, K		$+$	increase
$\dot{E}$	Exergy rate, W		$-$	decrease
$\dot{S}$	Entropy rate, W/K		ch	chemical
e	specific exergy, J/kg		kin	kinetic
h	specific enthalpy, J/kg		m	mechanical
i	chemical component		ph	physical
j	stream		pot	potential
k	component		t	thermal
p	pressure, Pa		*Subscripts*	
s	specific entropy, J/(kg·K)		0	dead state
x	mass fraction		cool	cooling
y	component/sub-system exergy ratio		cv	control volume
Abbreviations			d	destruction
GOR	Gas-to-oil Ratio		f	fuel
LNG	Liquefied Natural Gas		feed	feed
NHV	Net Heating Value, J/kg		gen	generation
OP	Overall Plant		h	hypothetical
PP	Processing Plant		heat	heating
TEG	Triethylene Glycol		in	inlet
WOR	Water-to-oil Ratio		l	loss
Greek letters			mix	mixture
β	chemical exergy correction factor		mt	metal
ε	exergy efficiency		out	outlet
Superscripts			p	product
$\wedge$	partial molar		tr	transit
$*$	relative		u	useful
Q	heat		w	waste
W	work			

because it pinpoints the locations and types of the irreversibilities taking place within a given system. As emphasised by Rivero [3], the application of the exergy concept in the petroleum industry would provide more detailed and consistent information on the performance of petrochemical systems. The exergy concept was introduced in the literature along with the concept of exergy efficiency, which aims at measuring the degree of thermodynamic perfection of the process under investigation.

Formulations of exergy-based criteria of performance have been proposed from the middle of the 20th century, with amongst others the contributions of Nesselmann [4] and Fratzscher [5,6]. Both works reported the definition of the exergy efficiency of a given system as the ratio of its total exergy output to its total exergy input, and they discussed the advantages and drawbacks of such formulation. Grassmann [7] and Nesselmann [8] suggested to define the exergy efficiency as the ratio of the part of the exergy transfers that contribute to the transformations taking place, i.e. *consumed* exergy, to the part of the exergy transfers that are generated within the system, i.e. *produced* exergy. Baehr [9,10] worked further on this concept, and stressed the difficulties of providing a non-ambiguous definition of an exergy efficiency, as different views on *consumed* and *produced* exergies may apply.

Further advances within this field include the studies of Brodyansky [11], Szargut [12–14], Kotas [15] and Tsatsaronis [16,17]. Brodyansky [11] suggested a systematic procedure for calculating the *produced* and *consumed* exergies, without regarding whether they are useful to the owner of the system. His work was based on the concept of *transit exergy* introduced by Kostenko (cf. Brodyansky [11]) and discussed also by Sorin et al. [18]. Szargut [12–14], Kotas [15] and Tsatsaronis [16,17] proposed to consider only the exergy transfers representing the *desired* exergetic output and the *driving* exergetic input of the system, leading to the concept of *product* and *fuel* exergies. Such considerations must be consistent with the purpose of owning and operating the system of investigation [19–22], both from an economic and a thermodynamic prospect. Lazzaretto and Tsatsaronis [23,24] suggested a systematic procedure for defining the exergy efficiency at a process component level. However, at a process level, a unique formulation may not be available and several expressions may be appropriate [16].

Various expressions of exergy efficiency for separation systems have been presented in the literature [11, 15,16,25]. Cornelissen [26] investigated three formulations for an air separation unit and a crude distillation plant. Different results were obtained, illustrating the variations and lack of uniformity across the exergy efficiency definitions [9,10,27]. Oliveira and Van Hombeeck [28] presented an exergy analysis of a Brazilian offshore platform, with another formulation of the exergy efficiency. This formulation was also used by Voldsund et al. [29] for a Norwegian offshore platform. Rian and Ertesvåg [30] studied a liquefied natural gas (LNG) plant using an exergy efficiency formulated particulary for LNG plants.

The literature seems to contain little, if nothing, on a uniform performance parameter for petroleum processes. In this paper we present a formulation of exergy efficiency that can be used on all types of such processes. The work was carried out in three main steps:

- a literature review of formulations of exergy efficiency for various petroleum processes was performed;

- the corresponding expressions were applied on the processing plants on four different offshore platforms;

- a new formulation was derived, based on the experience from the two first steps.

This paper is structured as follows: Section 2 presents the four oil and gas platforms used as case studies in this work. Section 3 describes the theoretical background, and Section 4 presents definitions of exergy efficiencies found in the literature, and their applicability to the four platforms is discussed. In Section 5, the derivation of a new exergy efficiency suitable for petroleum separation processes is described, together with the application of this efficiency to the four platforms. The outcomes are criticised in Section 6, and concluding remarks are outlined in Section 7.

2. System description

2.1. General overview

Offshore platforms are large structures with facilities to extract and process petroleum from subsea reservoirs. Petroleum is processed in a processing plant where power and heat are consumed. The power is

produced by gas turbines fuelled with a fraction of the produced gas, or alternatively heavy oil or diesel. The heating demand, if one, is either met by using fuel gas burners, electric heaters or by waste heat recovery from the utility plant. A schematic overview of the processing and utility plants are given in Figure 1. This work focuses on the processing plant, but the reasoning presented in this work can be extended to the complete platform.
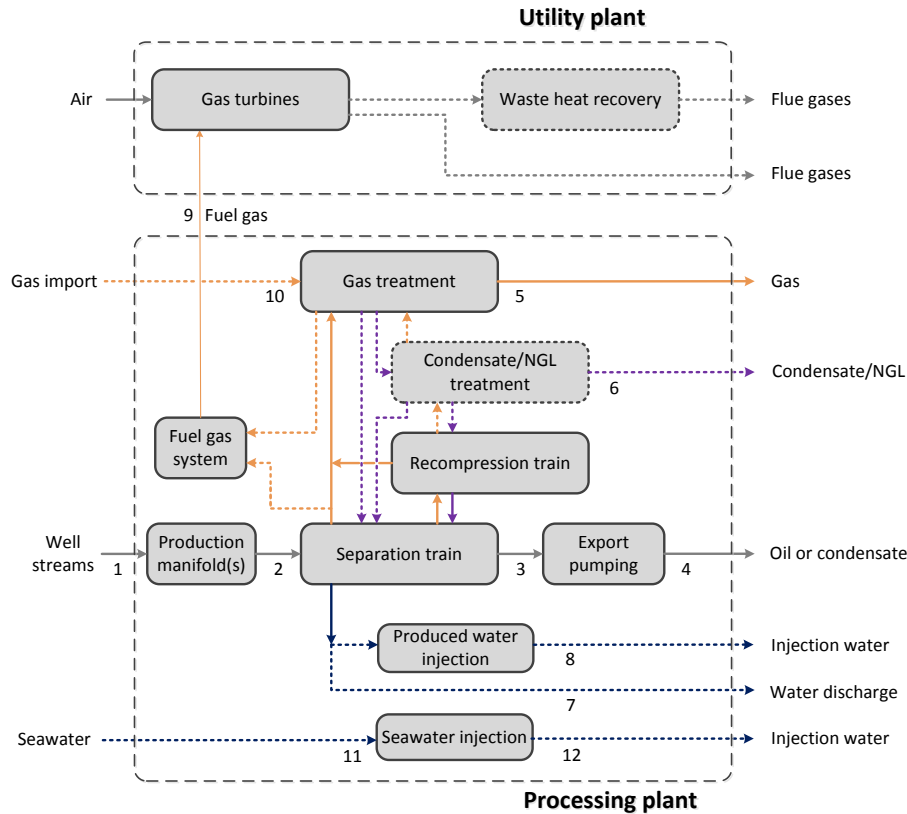

Figure 1: General overview of the processing and power plants.

Petroleum is a complex multiphase mixture: it contains a large spectrum of chemical components, from light hydrocarbons in gaseous form (e.g. methane) to heavy ones in liquid phase (e.g. naphtenes and cycloalkanes) and is extracted along with subsurface water. The aim of the processing plant is to separate efficiently the different phases to satisfy the different process and export constraints, and to maximise the hydrocarbon production. Crude oil consists mostly of medium- to heavy hydrocarbons, while natural gas mostly consists of light-weight alkanes. Differences across offshore platforms can be summarised as follows, as summarised in Refs. [31–38]:

- reservoir characteristics (e.g. initial temperature and pressure);

- fluid properties (e.g. chemical composition, gas- and water-to-oil (GOR and WOR) ratios);

- product requirements (e.g. export pressure and temperature, chemical purity);

- operating strategies (e.g. oil and gas recovery, gas treatment, condensate export).

These differences induce variations in temperatures, pressures and flow rates throughout the system as well as in demands for compression, heating, cooling, dehydration, desalting and sweetening. The structural design of the processing plant stays nevertheless similar.

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In the processing plant, oil, gas and water enter one or several production manifolds in which the well-fluid streams are mixed and the pressure reduced to ease separation between the liquid and gaseous phases. The well-fluid streams are fed into a separation system where oil, gas and water are separated by gravity in one or more stages, with throttling in between. Crude oil leaving the separation train enters a treatment and export pumping section. Gas leaving the separation and oil pumping steps enters the recompression train. It is cooled, sent to a scrubber where condensate and water droplets are removed, and recompressed to the pressure of the previous separation stage. It is then sent to the gas treatment train, where it is purified and possibly dehydrated by TEG (triethylene glycol). Gas may be compressed for export to the shore, lift or injection.

Condensate removed from the recompression and gas treatment trains is (i) either sent back to the separation train and mixed with crude oil or (ii) processed in a condensate treatment section. Produced water enters a wastewater handling train, in which suspended particulates and dissolved hydrocarbons are removed. It is then discharged into the sea or enters an injection train where it is further cleaned and pumped to a high pressure level. In parallel, seawater may be processed on-site for further injection into the reservoir for enhanced oil recovery.

The cooling demand is satisfied by using a direct cooling medium, e.g. seawater or air, or an indirect one, e.g. a glycol/water mixture. Heat exchanger networks between the different streams flowing through the system may also be integrated to promote heat integration.

Processes such as condensate treatment and natural gas liquid recovery are uncommon offshore, with only a few applications worldwide. Oil and gas treatment is generally limited to gas dehydration in the North Sea, whereas it also includes oil desalting and gas sweetening in the Gulf of Mexico. Further details on oil and gas processing can be found in the textbook of Manning et al. [39] and more specific information on North Sea platforms are given in Refs. [31,40].

2.2. Case studies

The four oil and gas platforms (Platforms A–D) investigated within this study are located in the North Sea region and present specific design characteristics (Table 1). Pressure levels of the most important process streams are given in Figure 2. Flowsheets of the processes plants on each of the platforms are given in the appendix.

Table 1: Comparison of the four offshore facilities discussed in this study. n means not-included and y means included.

Platform	A	B	C	D
System characteristics				
Age, years	20	10	10	20
Gas-to-oil ratio (standard volume basis)	2800	3200	360	230
Gas-to-oil ratio trend	↗	↗	↗	↘
System products				
Oil	export	none	export	export
Gas	fuel	fuel	fuel	fuel
	injection	export	injection	export
			import	
			lift	
Condensate	export	export	export	export
	(mixed with oil)		(mixed with oil)	(mixed with gas)
Produced water	discharge	injection	discharge	discharge
Seawater	cooling	cooling	cooling	cooling
				injection
				(complement)
Additional processes				
Dehydration	n	n	n	y
Condensate treatment	n	n	n	y
Water injection	n	n	n	y

These four platforms, although similar in terms of structural design (Figure 1), present significant differences in well-fluid processing and in operating conditions (Figure 2):

- the gas-to-oil ratio is either increasing (Platforms A, B and C), meaning that the gas treatment train is run at full-design conditions, or decreasing (Platform D), implying that this subsystem is run in off-design conditions, and that anti-surge recycling is practised to protect the compressors;

- platforms processing heavy and viscous crude oil (e.g. Platform C) or with a high propane content (e.g. Platform D) require heating in the separation train to enhance vapour-liquid separation and to meet the export specifications;

- the pressure at the final stage of the separation train (p_3) is constrained by the maximum allowable vapour pressure of the crude oil/condensate in the pipelines and shuttle tankers, and is below 3 bar for all platforms;

- the pressure of the produced oil/condensate at the outlet of the pumping section (p_4) is either higher (e.g. Platform C) or lower (e.g. Platforms A, B and D) than at the outlet of the production manifold (p_2);

- the pressure at the outlet of the gas treatment section (p_5) is either higher (e.g. Platforms A, C and D) or lower (e.g. Platform B) than at the inlet of the separation system (p_2). There is a need for gas compression in three of the four platforms.
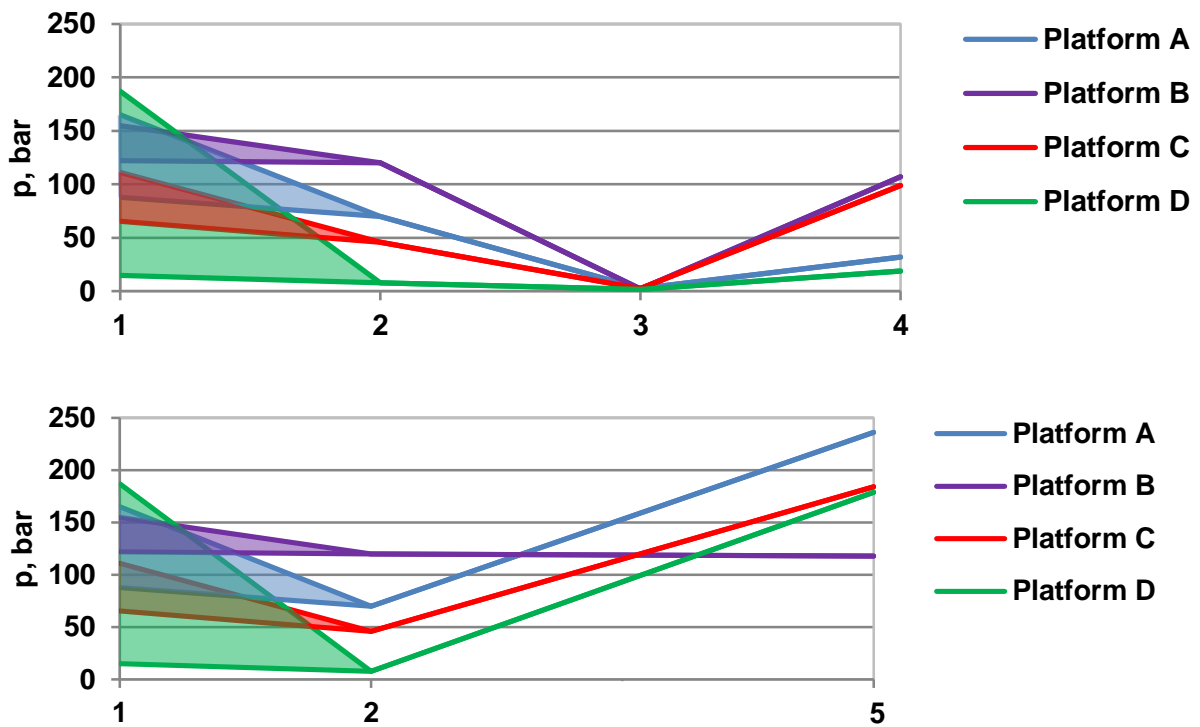

Figure 2: Schematic overview of the pressure levels from the feed to the oil and gas within the four offshore platforms under study.

For more details about the processes taking place on each of these platforms, the reader is referred to several works conducted by the same authors [41–43].

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2.3. Modelling and simulation

The process simulations were carried out with Aspen HYSYS® [44] and Aspen Plus® version 7.2 [45], with the exception of the glycol dehydration system. Simulations of the production manifolds, petroleum separation, oil pumping, gas recompression and flaring were based on the Peng-Robinson and Soave-Redlich-Kwong equations of state [46,47]. The water purification and injection processes were simulated based on the Non-Random Two Liquid model [48] and the dehydration process on the Schwartzentruber-Renon equation of state [49,50].

3. Theoretical background

3.1. Exergy analysis

Exergy is defined as the maximum theoretical useful work as the system is brought into complete thermodynamic equilibrium with the environment [12]. In this work, the discussions on exergy efficiencies focus exclusively on the exergy associated with mass and energy transfers.

Unlike energy, exergy is not conserved in real processes – some is destroyed due to internal irreversibilities. On a time rate form and for a control volume with in- and outgoing flows, the exergy balance is expressed as:

$$\dot{E}_d = \sum \dot{E}_{in} - \sum \dot{E}_{out}$$
$$= \sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_{in}e_{in} - \sum \dot{m}_{out}e_{out} \tag{1}$$

where $\dot{E}_d$ is the exergy destroyed inside the control volume, $\dot{E}_{in}$ is *all* exergy entering the system and $\dot{E}_{out}$ is *all* exergy leaving it. The symbol $\dot{m}$ denotes the mass flow rate of a stream of matter, $\dot{Q}_k$ and $\dot{W}$ the time rates of energy transfer by heat and work ($\dot{Q} \geq 0$ indicates heat transfer to the system, $\dot{W} \geq 0$ work done by the system) and e the specific exergy of a stream of matter. The symbols T_0 and T_k denote the environmental temperature and the local temperature where heat transfer takes place. The subscripts in and out denote the inlet and outlet of the system and k the boundary of the component. The exergy destruction rate can also be calculated from the Gouy-Stodola theorem, which is expressed as:

$$\dot{E}_d = T_0\dot{S}_{gen} \tag{2}$$

where $\dot{S}_{gen}$ is the entropy generation rate inside the control volume.

Exergy destruction is also called *internal exergy losses*, since this is exergy that is lost because of the irreversibilities taking place *inside* the control volume under study. The exergy discharged to the environment without any practical use (e.g. exergy content of exhaust gases from a gas turbine – exergy transferred to the cooling water) is referred to as *external exergy losses* or just *exergy losses* [21,51]. This waste exergy is destroyed when mixed irreversibly with the environment.

3.2. Flow exergy

In the absence of nuclear, magnetic and electrical interactions, the exergy associated with a stream of matter is a function of its physical e^{ph}, chemical e^{ch}, kinetic e^{kin} and potential e^{pot} components [21]. The molar exergy of a material stream is expressed as:

$$e = e^{ph} + e^{ch} + e^{kin} + e^{pot} \tag{3}$$

In this work, kinetic and potential contributions on the flow exergies are assumed to be negligible compared to physical and chemical exergies.

Physical exergy accounts for temperature and pressure differences from the environmental state and is defined as:

$$e^{\mathrm{ph}} = (h - h_0) - T_0(s - s_0) = \underbrace{h - h(T_0, p) - T_0\left(s - s(T_0, p)\right)}_{\mathrm{I}} + \underbrace{h(T_0, p) - h_0 - T_0\left(s(T_0, p) - s_0\right)}_{\mathrm{II}} \quad (4)$$

where h and s are the specific enthalpy and entropy of a stream of matter, respectively. Terms I and II refer to the the temperature-based and pressure-based components of the physical exergy [15], respectively, and are also named thermal and mechanical exergies [16].

Chemical exergy accounts for deviations in chemical composition from reference substances present in the environment. In this work, chemical exergy is calculated using the reference environment defined in Szargut [12,52,53]. The specific chemical exergy of a given mixture $e_{\mathrm{mix}}^{\mathrm{ch}}$ is expressed as [54]:

$$e_{\mathrm{mix}}^{\mathrm{ch}} = \underbrace{\sum_i x_i e_{i,\mathrm{mix}}^{\mathrm{ch}}}_{\mathrm{I}} = \underbrace{\sum_i x_i e_{i,0}^{\mathrm{ch}}}_{\mathrm{II}} + \underbrace{\left(\sum_i x_i \left(h_{i,\mathrm{mix}} - h_{i,0}\right)\right) - T_0\left(\sum_i x_i \left(s_{i,\mathrm{mix}} - s_{i,0}\right)\right)}_{\mathrm{III}} \quad (5)$$

where the mass fraction, the chemical component and the mixture are denoted by x, i and mix, respectively. The specific exergy of a given chemical component is written $e_{i,\mathrm{mix}}^{\mathrm{ch}}$ when it is in the mixture and $e_{i,0}^{\mathrm{ch}}$ when it is in a pure component state. The term I illustrates the chemical exergy of each individual chemical component in the mixture, the term II the chemical exergy of these components in an unmixed form and the term III the reduction in chemical exergy due to mixing effects.

If no chemical transformations are taking place within a separation system, the terms related to the chemical exergy of pure components cancel and the change in chemical exergy is equal to the exergy used to perform the separation work [15].

The specific chemical exergy of hypothetical components $e_{\mathrm{h}}^{\mathrm{ch}}$ is determined with the heuristic correlations of Rivero [55]:

$$e_{\mathrm{h}}^{\mathrm{ch}} = \beta \mathrm{NHV}_{\mathrm{h}} + \sum x_{\mathrm{mt}} e_{\mathrm{mt}}^{\mathrm{ch}} \quad (6)$$

where NHV stands for Net Heating Value, x_{mt} for the mass fraction of metal impurities, $e_{\mathrm{mt}}^{\mathrm{ch}}$ for the corresponding chemical exergy and β for the chemical exergy correction factor.

3.3. Exergy efficiency

The definitions of exergy efficiency, as presented and discussed in the open literature, can be divided into two main groups, as suggested by Lior and Zhang [27]:

- the *total*, *overall*, *input-output* or *universal* exergy efficiency, which is defined as the ratio of all outgoing to ingoing exergy flows;

- the *task*, *utilitarian*, *consumed-produced*, *rational* or *functional* exergy efficiency, which is defined as the ratio of the exergy terms associated with the products generated within the system, i.e. the *produced exergy*, to the exergy terms associated with the resources expended to achieve these outputs, i.e. the *consumed exergy*.

3.3.1. Total exergy efficiency

For a given open thermodynamic system at steady-state, the exergy balance can be expressed as:

$$\sum \dot{E}_{\mathrm{in}} = \sum \dot{E}_{\mathrm{out}} + \dot{E}_{\mathrm{d}} = \sum \dot{E}_{\mathrm{out,u}} + \sum \dot{E}_{\mathrm{out,l}} + \dot{E}_{\mathrm{d}} \quad (7)$$

where $\dot{E}_{\mathrm{in}}$ and $\dot{E}_{\mathrm{out}}$ are the exergy inputs and outputs to and from the system, associated with streams of matter and of energy, and $\dot{E}_{\mathrm{d}}$ the exergy destruction. The exergy output consists of useful exergy output $\dot{E}_{\mathrm{out,u}}$, and exergy that is lost $\dot{E}_{\mathrm{out,l}}$ (i.e. the exergy of waste products that is not taken into use, but discharged to the environment).

The *total* exergy efficiency ε_I is defined as the ratio of all exergy outflows to inflows [26,27,56]:

$$\varepsilon_{I-1} \equiv \frac{\sum \dot{E}_{\text{out}}}{\sum \dot{E}_{\text{in}}} = 1 - \frac{\dot{E}_{\text{d}}}{\sum \dot{E}_{\text{in}}} \tag{8}$$

where some authors exclude the exergy associated with waste products [6,56]:

$$\varepsilon_{I-2} \equiv \frac{\sum \dot{E}_{\text{out,u}}}{\sum \dot{E}_{\text{in}}} = 1 - \frac{\dot{E}_{\text{out,l}} + \dot{E}_{\text{d}}}{\sum \dot{E}_{\text{in}}} \tag{9}$$

The *total* exergy efficiency is claimed to be adequate when (i) the ingoing and outgoing exergy flows are converted to other forms of exergy [26] or (ii) a major part of the out-flowing exergy can be considered as useful, as it is the case of power plants [27] or (iii) for dissipative processes and devices [15,57].

3.3.2. Task exergy efficiency

The concept of *total* exergy efficiency has been criticised, as it takes into account all the exergetic flows entering and exiting a system, without considering whether they are utilised in the thermodynamic conversions. The *task* exergy efficiency, on the contrary, differentiates the exergy flows undergoing transformations from the exergy flows that are not affected, i.e. neither used nor produced. Grassmann [7] proposed a general formulation for an exergy efficiency: he suggested the ratio of the intended increase to the used decrease in ability to do work. In exergy terms, this means that the exergy efficiency should be defined as the ratio of the production of exergy that is desired, to the reduction of exergy that is utilised. It was emphasised that this performance criterion always has a value between 0 and 1, as the increased ability to do work always is smaller than the decreased ability.

Baehr [10] proposed a variant of this formulation, considering *all* the exergy increases in the numerator and *all* the exergy decreases in the denominator. At the difference of the expression proposed by Grassmann [7], the total production and expenditure of exergy are considered, whether they are actually desired or utilised within the system. It was pointed out that (i) exergy efficiencies based on exergy differences are more sensitive to changes in the system than the total exergy efficiency and are therefore more suitable and (ii) different numerical values could be obtained with the formulation of exergy efficiency proposed by Grassmann [7], as it depends on whether an exergy difference is considered as *useful, used* or none of those.

Szargut [12,14,58], and Kotas [15,20] argued that the exergy efficiency should be defined as the ratio of (i) the *desired output* or *useful exergetic effect* and (ii) the *necessary input* or *driving exergy expense*. Other authors name the same terms *exergetic product* $\dot{E}_{\text{p}}$ and *exergetic fuel* $\dot{E}_{\text{f}}$ [21,51]. The exergetic balance (Equation 1) can be rewritten:

$$\dot{E}_{\text{p}} = \dot{E}_{\text{f}} - \dot{E}_{\text{l}} - \dot{E}_{\text{d}} \tag{10}$$

Hence, the task exergy efficiency can be written:

$$\varepsilon \equiv \frac{\dot{E}_{\text{p}}}{\dot{E}_{\text{f}}} = 1 - \frac{\dot{E}_{\text{l}} + \dot{E}_{\text{d}}}{\dot{E}_{\text{f}}} \tag{11}$$

Brodyansky [11] and Sorin [18] proposed to define the exergy efficiency as the ratio of the total exergy output to the total exergy input, minus the *transit exergy* $\dot{E}_{\text{tr}}$ in both numerator and denominator.

$$\varepsilon \equiv \frac{\sum \dot{E}_{\text{out}} - \sum \dot{E}_{\text{tr}}}{\sum \dot{E}_{\text{in}} - \sum \dot{E}_{\text{tr}}} \tag{12}$$

The concept of *transit exergy* was introduced by Kostenko [59], and it was further developed by Brodyansky [11]. The transit exergy is the part of the exergy supplied to a system that flows through the system without undergoing any physical or chemical transformation. The concept of transiting exergy is also mentioned by Cornelissen [26], who applied this method to an air separation unit and a crude oil distillation plant. The lack of ambiguity and the complexity of the calculations were underlined, as this method requires a precise decoupling of the exergy flows into their components. This efficiency can also be regarded as a variant of the *total* exergy efficiency.

4. Exergy efficiencies for petroleum processes

In this section, we conduct a literature survey of the derivations of exergy efficiencies for petroleum processing systems in general. We apply them to our four offshore processing plants and discuss their relevance. An overview of the relevant definitions is given in Section 4.1, while each of them is derived for offshore processing plants and discussed in detail in Sections 4.2–4.5. The exergy efficiencies for the utility plant, which consists of gas turbines, and possibly of a waste heat recovery system, are not within the scope of this work, as they are well-established definitions that can be found in the literature (see e.g. [15]).

4.1. Overview

Several approaches for the exergy efficiencies of petroleum processing systems can be found in the literature [15,17,26,28–30,60]. In addition to the *total* exergy efficiency, three different *task* exergy efficiencies are found. The concepts of the *task* exergy efficiency formulations are summarised in Table 2. For the types of *task* efficiencies where it is possible both to include waste streams as product or as loss, we have chosen to systematically regard the exergy associated with them as lost exergy.

Table 2: The concept of three *task* exergy efficiencies found in the literature for petroleum systems.

System	Reference	Fuel	Product
General separation	[15]	Added heat and work	Physical and chemical exergy changes
Offshore platform	[28,41]		
LNG plant	[30]	Added heat and work	Chemical exergy increase
Crude oil distillation	[26]	+ input physical exergy	+ output physical exergy
Distillation column	[60]	Added heat and work	Chemical exergy increase
		+ physical exergy decreases	+ physical exergy increases

Figure 3 shows schematically the exergy streams entering and leaving the processing plant, as well as the utility plant, and clarifies the notation used in the following sections.
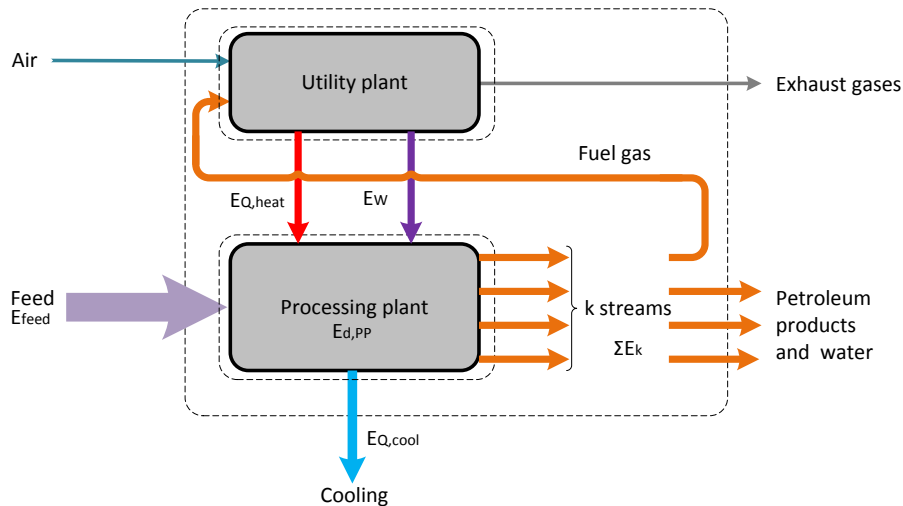

Figure 3: Schematic overview of exergy streams entering and exiting the processing and utility plants.

4.2. Total exergy efficiency

The exergy balance for the processing plant of the oil and gas facility can be expressed as:

$$\underbrace{\dot{E}_{\text{feed}} + \dot{E}^Q_{\text{heat}} + \dot{E}^W}_{\dot{E}_{\text{in}}} = \underbrace{\sum_{k,\text{u}} \dot{E}_{k,\text{u}}}_{\dot{E}_{\text{out,u}}} + \underbrace{\sum_{k,\text{w}} \dot{E}_{k,\text{w}} + \dot{E}^Q_{\text{cool}}}_{\dot{E}_{\text{out,l}}} + \underbrace{\dot{E}_{\text{d,PP}}}_{\dot{E}_{\text{d}}} \tag{13}$$

The left-hand side terms consist of the exergy associated with the feed entering the processing plant $\dot{E}_{\text{feed}}$ (i.e. reservoir fluid) and the heat exergy $\dot{E}^Q_{\text{heat}}$ and power exergy $\dot{E}^W$ delivered by the utility plant. The right-hand side terms consist of the exergy of the useful outlet material streams of the processing plant $\sum_k \dot{E}_{k,\text{u}}$ (i.e. oil, gas, condensate, fuel gas), the wasted outlet material streams $\sum_k \dot{E}_{k,\text{w}}$ (i.e. flared gas, produced water), the exergy lost in the cooling system $\dot{E}^Q_{\text{cool}}$ and the destroyed exergy $\dot{E}_{\text{d,PP}}$. All the left-hand side terms include the input exergy E_{in}, while the useful outlet material streams on the right-hand side are counted as useful output exergy $E_{\text{out,u}}$. The produced water that is extracted along with oil and gas is normally considered as waste, since it is discharged to the surroundings without being used. The exception to this rule is if the produced water is injected back for enhanced oil recovery, which is a possible plan in the case of Platform D.

The *total* exergy efficiency without differentiating the *useful* from the *waste* streams [4] is:

$$\varepsilon_{I-1} = \frac{\sum_{k,\text{u}} \dot{E}_{k,\text{u}} + \sum_{k,\text{w}} \dot{E}_{k,\text{w}} + \dot{E}^Q_{\text{cool}}}{\dot{E}_{\text{feed}} + \dot{E}^Q_{\text{heat}} + \dot{E}^W} \tag{14}$$

while the *total* exergy efficiency considering only the *useful* streams is:

$$\varepsilon_{I-2} = \frac{\sum_{k,\text{u}} \dot{E}_{k,\text{u}}}{\dot{E}_{\text{feed}} + \dot{E}^Q_{\text{heat}} + \dot{E}^W} \tag{15}$$

The total exergy efficiencies of all four processing plants (Table 3) range between $99\% - 100\%$ when waste streams are considered as a part of the product and between $98\% - 100\%$ when waste streams are considered lost (Figure 4). The facility that presents the highest efficiency is Platform B, as gas is not compressed before export and little power is required on-site.

Table 3: *Total* exergy efficiencies (%) without differentiating between waste useful streams and waste streams ε_{I-1} and with waste streams regarded as lost ε_{I-2}.

	Platform A	Platform B	Platform C	Platform D
ε_{I-1}	99.7	99.9	99.9	99.6
ε_{I-2}	99.5	99.8	99.8	98.0

The high numbers are caused by the inclusion of the chemical exergy of hydrocarbons in the formulation of these exergy efficiencies, and the total efficiencies are therefore always high. They can hardly be used to compare the performance of oil and gas facilities, since (i) they give the impression that all platforms are similar in terms of efficiency and (ii) they are poorly sensitive to improvement efforts.

Kotas [15] and Tsatsaronis [16] support this view in their works. They argue that the total exergy efficiencies do not show the potential for reducing the system inefficiencies, and that conclusions based on them would be misleading. Another critique on the total exergy efficiencies is that they do not reflect the *purposes* of operating these facilities, which are to separate the petroleum from the water, and to export the oil and gas to the shore.

The same reasoning can be drawn for the energy efficiency that is used for evaluation of some oil and gas platforms. On Platform D this parameter has varied between 92% and 94% these last years, although the flows of exported oil and gas have changed from day-to-day, and that flaring and venting was significantly reduced. This indicator provides limited information when the performance of an oil and gas system is analysed over time.
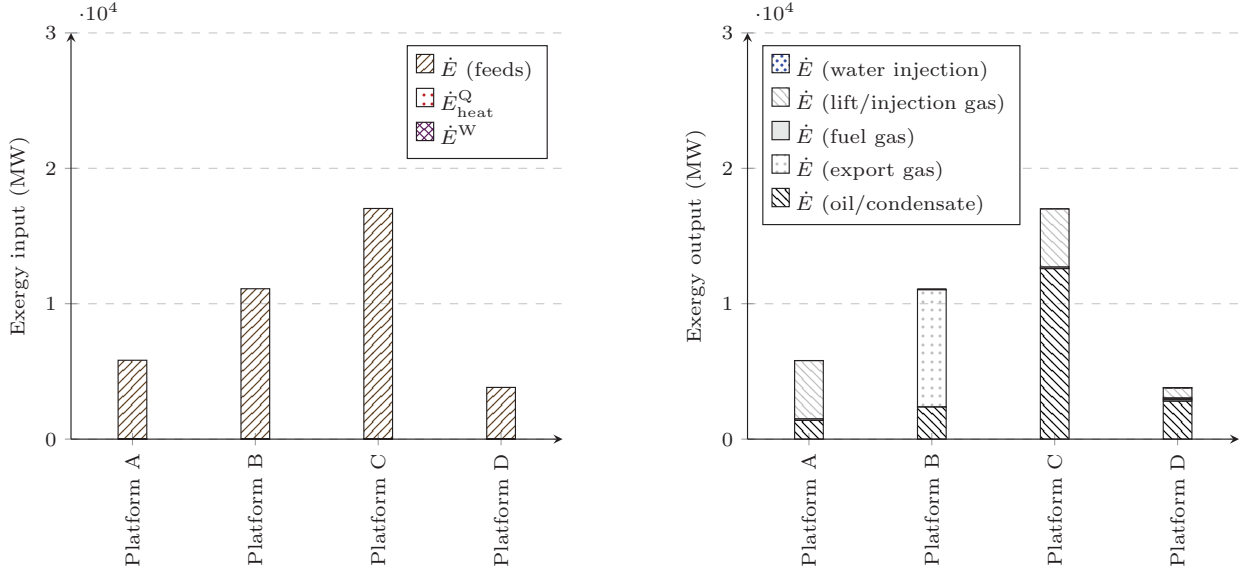
Figure 4: Exergy input and useful output flows.

4.3. Task exergy efficiency: Kotas for general separation systems, Oliveira for offshore platform

The exergy balance for the processing plant, Equation 13, can be rewritten as:

$$\underbrace{\dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}}_{\dot{E}_{\text{f}}} = \underbrace{\left(\sum_{k} \dot{E}_{k} - \dot{E}_{\text{feed}}\right)}_{\dot{E}_{\text{p}}} + \underbrace{\dot{E}_{\text{cool}}^{Q}}_{\dot{E}_{\text{l}}} + \underbrace{\dot{E}_{\text{d,PP}}}_{\dot{E}_{\text{d}}} \tag{16}$$

The left-hand side terms can be identified as the resources required to drive the processing plant, i.e. the exergetic fuel $\dot{E}_{\text{f}}$, while the difference of exergy between the inlet and outlet material streams can be considered as the exergetic product $\dot{E}_{\text{p}}$. This approach is similar to the one suggested by Kotas [15] and used by Oliveira and Van Hombeeck [28] for petroleum separation processes on a Brazilian offshore platform, and used for the processing plant of an North Sea oil platform by Voldsund et al. [29].

This approach considers that the desired effect of the offshore platforms is the difference of exergy between the inlet and outlet streams, i.e. the exergy increase due to separation, and possibly the exergy increase with physical processes such as compression. The resources required to drive the processing plant and to separate the three phases correspond to the power and heat required on-site. The losses are identified as the exergy lost with the cooling water $\dot{E}_{\text{l}}$ and the rest is the destroyed exergy $\dot{E}_{\text{d}}$.

The expression for this exergy efficiency, denoted ε_{II-1}, is then given by:

$$\varepsilon_{II-1} = \frac{\sum_{k} \dot{E}_{k} - \dot{E}_{\text{feed}}}{\dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}} = 1 - \frac{\dot{E}_{\text{cool}}^{Q} + \dot{E}_{\text{d,PP}}}{\dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}} \tag{17}$$

which is similar to the expression of the rational efficiency for a generalised separation plant [15].

Calculating the exergy efficiency with Equation 17 (Table 4), it can be seen that most exergy ($> 85\,\%$) consumed in the processing plant corresponds to the power produced in the gas turbines (Figure 5). This power consumption is related to the compression and pumping demands on-site. The consumption of thermal exergy is negligible in two cases, since heating is only required in the fuel gas system, where power is used to drive electric heaters.

The exergy efficiencies as defined in Equation 17 for the processing plants of Platforms A, C and D are relatively low ($\simeq 13$-$24\,\%$). This is in accordance with the findings of Kotas [15], who suggested that the
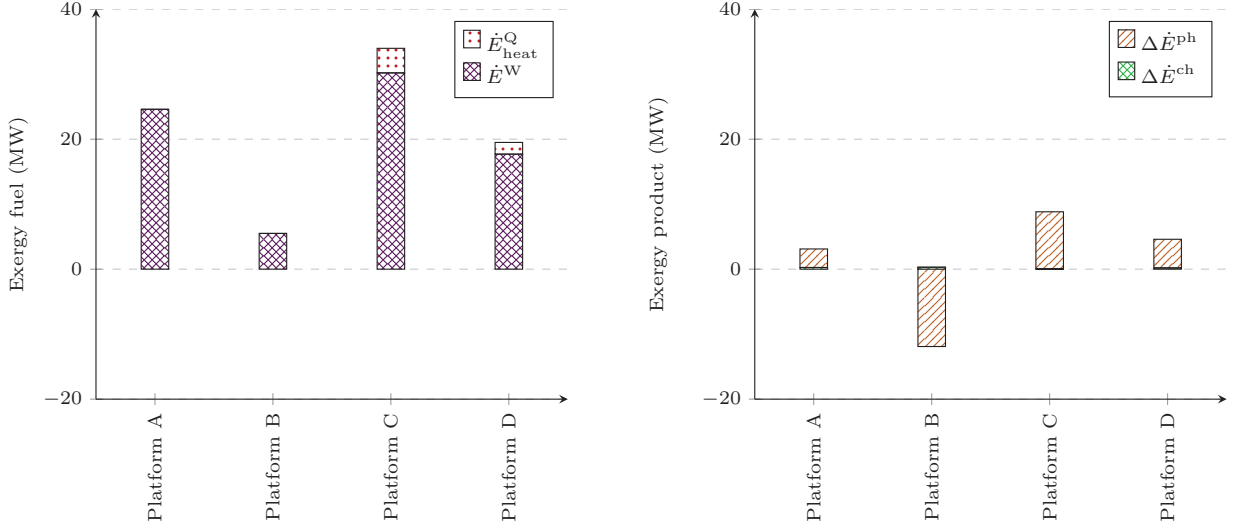
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Figure 5: Exergy fuels and products, based on the approach of Kotas [15] and Oliveira and Van Hombeeck [28] for generic separation systems.

Table 4: Task exergy efficiencies (%) based on the approach of Kotas [15] and Oliveira and Van Hombeeck [28] for generic separation systems.

	Platform A	Platform B	Platform C	Platform D
ε_{II-1}	12.7	-215	20.6	23.6

rational efficiency of separation processes is often low, because of the large compression ratios of the gas streams.

Platform B presents a negative efficiency, since the exergy of the output streams is smaller than the exergy of the feeds. The pressures and temperatures of the oil and gas are lower than those of the feed since there is no need for gas compression before export. The reductions of physical exergy ($\simeq 12{,}200\,\text{kW}$) are thus higher than the increases of chemical exergy ($\simeq 300\,\text{kW}$), leading to the negative value. The same has been seen when this definition of the exergy efficiency has been applied at the level of the separation module for another platform [29].

This case illustrates the limitations of applying this approach for evaluation of our four different processing plants, and suggests that the differences of physical and chemical exergy between the input and output streams should be considered apart. The reduction of pressure throughout the platform results in a higher vapour fraction of the streams and drives the separation. The expense of physical exergy may therefore be accounted as a part of the resources spent to drive the processing plant.

4.4. Task exergy efficiency: Cornelissen for crude oil distillation, Rian and Ertesvåg for LNG plant

Kotas [15] suggested an alternative to Equation 17 for air distillation plants, where the physical and chemical exergy in the material streams are treated separately:

$$\underbrace{\dot{E}_{\text{feed}}^{\text{ph}} + \dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}}_{\dot{E}_{\text{f}}} = \sum_{k} \dot{E}_{k}^{\text{ch}} - \dot{E}_{\text{feed}}^{\text{ch}} + \sum_{k} \dot{E}_{k,\text{u}}^{ph} + \sum_{k} \dot{E}_{k,\text{w}}^{ph} + \dot{E}_{\text{cool}}^{Q} + \dot{E}_{\text{d,PP}}$$

$$= \underbrace{\Delta E^{\text{ch}} + \sum_{k,\text{u}} \dot{E}_{k,\text{u}}^{ph}}_{\dot{E}_{\text{p}}} + \underbrace{\sum_{k,\text{w}} \dot{E}_{k,\text{w}}^{ph} + \dot{E}_{\text{cool}}^{Q}}_{\dot{E}_{\text{l}}} + \underbrace{\dot{E}_{\text{d,PP}}}_{\dot{E}_{\text{d}}} \qquad (18)$$

The exergetic fuel is now taken as the sum of the exergy transferred as heat and power and the physical exergy of the feed. Similarly, the exergetic product is now taken as the difference of chemical exergies between the inlet and outlets of the processing plant, as well as the physical exergy of the useful output streams.

This approach is similar to the one applied by Cornelissen [26] for a crude oil distillation plant and by Rian and Ertesvåg [30] for an LNG plant, where it is suggested that all physical exergy of the feed streams is consumed along with exergy associated with heat and power. The desired result is taken as the physical exergy of the outlet streams, as well as the increased chemical exergy due to separation.

The expression for the exergy efficiency of the system (ε_{II-2}) is then given by:

$$\varepsilon_{II-2} = \frac{\Delta E^{\text{ch}} + \sum_{k,\text{u}} \dot{E}_{k,\text{u}}^{\text{ph}}}{\dot{E}_{\text{feed}}^{\text{ph}} + \dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}} = 1 - \frac{\sum_{k,\text{w}} \dot{E}_{k,\text{w}}^{ph} + \dot{E}_{\text{cool}}^{Q} + \dot{E}_{\text{d,PP}}}{\dot{E}_{\text{feed}}^{\text{ph}} + \dot{E}_{\text{heat}}^{Q} + \dot{E}^{W}} \tag{19}$$

When applying this approach (Table 5, Figure 6), the exergetic fuel amounts from $33\,\text{MW}$ (Platform D) to $110\,\text{MW}$ (Platform B). The major contributions to the fuel are the physical exergy of the feeds and the power consuption. In any case, it can be seen that most exergy consumed on the plant is used to produce high-pressure gas, and that the separation effect is negligible in comparison.
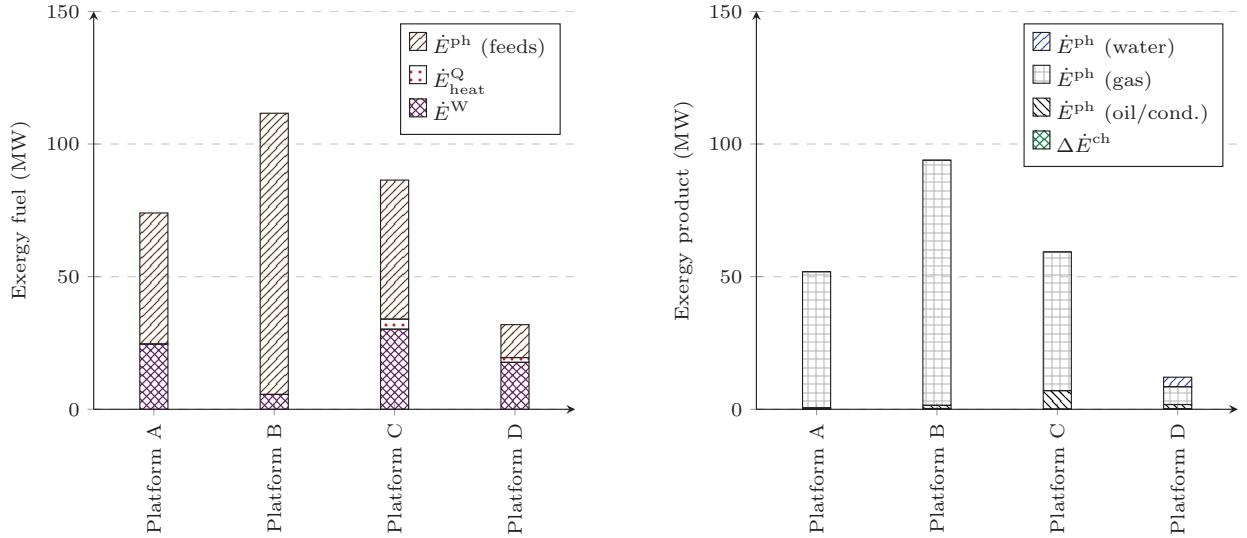

Figure 6: Exergy fuels and products, based on the approach of Cornelissen [26] and Rian and Ertesvåg [30] for crude oil distillation and LNG plants.

Table 5: Task exergy efficiencies (%) based on the approach of Cornelissen [26] and Rian and Ertesvåg [30] for crude oil distillation and LNG plants.

	Platform A	Platform B	Platform C	Platform D
ε_{II-2}	70.9	84.2	71.0	33.2

The platform that presents the highest exergy efficiency, as defined in Equation 19, is Platform B ($\simeq 84\,\%$), followed by Platforms A ($\simeq 71\,\%$), C ($\simeq 71\,\%$) and D ($\simeq 33\,\%$). The higher performance of Platform B can be explained by the high rate of physical exergy transiting throughout the plant with the produced gas. Gas is exported at nearly the same conditions as it enters, and its physical exergy dominates transformations taking place on-site. On the opposite side, Platform D presents a smaller exergy efficiency, because the lift and export pressures ($\simeq 175$–$180\,\text{bar}$) are much higher than the feed pressures ($\simeq 11$–$45\,\text{bar}$) and the separation pressures ($\simeq 1.7$–$8\,\text{bar}$). Significant amount of power is required to increase the gas pressure,

which results in high irreversibilities in the gas compression section. Moreover, the water cut of the feeds is much higher ($\simeq 85$–95% on a molar basis), and the produced water is currently discharged to the sea at high temperatures, and thus high physical exergies ($\simeq 6.1\,\mathrm{MW}$), without being further used.

When this approach was used for an LNG plant, most physical exergy entering the system was pressure-based, and most leaving the system was temperature-based. This is different in the present cases, where most physical exergy that enters and exits is pressure-based, and has not necessarily undergone exergy transformations within the process.

4.5. Task exergy efficiency: Tsatsaronis and Cziesla for distillation columns

In the third alternative formulation of the *task* exergy efficiency, the fuel exergy is defined as the sum of the physical exergy decreases between the inflowing feed and the separated streams with a lower specific physical exergy (k^-) and the exergy associated with heating and power. The product exergy is defined as the sum of the physical exergy increases between the inflowing feed and the separated useful products with a higher specific physical exergy (k^+) and the chemical exergy increases between the feed and products. By separating between product streams with increased and decreased specific physical exergy, Equation 13 can be rewritten:

$$\underbrace{\sum_{k^-} \dot{m}_{k^-} \cdot (e_{\mathrm{feed}}^{\mathrm{ph}} - e_{k^-}^{\mathrm{ph}}) + \dot{E}_{\mathrm{heat}}^{Q} + \dot{E}^{W}}_{\dot{E}_{\mathrm{f}}} =$$
$$\underbrace{\Delta E^{\mathrm{ch}} + \sum_{k^+,\mathrm{u}} \dot{m}_{k^+,\mathrm{u}} \cdot (e_{k^+,\mathrm{u}}^{\mathrm{ph}} - e_{\mathrm{feed}}^{\mathrm{ph}})}_{\dot{E}_{\mathrm{p}}} + \underbrace{\sum_{k^+,\mathrm{w}} \dot{m}_{k^+,\mathrm{w}} \cdot (e_{k^+,\mathrm{w}}^{\mathrm{ph}} - e_{\mathrm{feed}}^{\mathrm{ph}}) + \dot{E}_{\mathrm{cool}}^{Q} + \underbrace{\dot{E}_{\mathrm{d,PP}}}_{\dot{E}_{\mathrm{d}}}}_{\dot{E}_{\mathrm{l}}} \tag{20}$$

The expression for the exergy efficiency of this system (ε_{II-3}) is then given by:

$$\varepsilon_{II-3} = \frac{\Delta E^{\mathrm{ch}} + \sum_{k^+,\mathrm{u}} \dot{m}_{k^+,\mathrm{u}} \cdot (e_{k^+,\mathrm{u}}^{\mathrm{ph}} - e_{\mathrm{feed}}^{\mathrm{ph}})}{\sum_{k^-} \dot{m}_{k^-} \cdot (e_{\mathrm{feed}}^{\mathrm{ph}} - e_{k^-}^{\mathrm{ph}}) + \dot{E}_{\mathrm{heat}}^{Q} + \dot{E}^{W}} = 1 - \frac{\sum_{k^+,\mathrm{w}} \dot{m}_{k^+,\mathrm{w}} \cdot (e_{k^+,\mathrm{w}}^{\mathrm{ph}} - e_{\mathrm{feed}}^{\mathrm{ph}}) + \dot{E}_{\mathrm{cool}}^{Q} + \dot{E}_{\mathrm{d,PP}}}{\sum_{k^-} \dot{m}_{k^-} \cdot (e_{\mathrm{feed}}^{\mathrm{ph}} - e_{k^-}^{\mathrm{ph}}) + \dot{E}_{\mathrm{heat}}^{Q} + \dot{E}^{W}} \tag{21}$$

which is similar to the expression of the exergy efficiency for a generalised distillation column, as discussed by Tsatsaronis and Cziesla [17].

The approach of Tsatsaronis and Cziesla considers the physical exergy decreases as part of the exergetic fuel, and the increases as part of the exergetic product, which is in accordance with the SPECO method proposed by Lazzaretto and Tastsaronis [23,24] and the previous works of Baehr [10] and Grassmann [7]. They define physical exergy decreases and increases by comparing the specific physical exergies of the outlet and inlet streams on a mass basis.

Calculating this efficiency on a mass basis (Table 6), suggests that Platform C presents the highest performance ($\simeq 54\%$), followed by Platforms A ($\simeq 48\%$), B ($\simeq 39\%$) and D ($\simeq 39\%$).

Table 6: Task exergy efficiencies (%) based on the approach of Tsatsaronis and Cziesla for distillation columns.

	Platform A	Platform B	Platform C	Platform D
$\varepsilon_{II-3,mass}$	48.1	39.0	53.9	38.8
$\varepsilon_{II-3,molar}$	38.2	1.7	49.3	39.3

The exergetic fuel includes two major contributions (Figure 7), which are the reduction in physical exergy and the power consumption. With the exception of Platform B, most exergetic fuel consists of the power input ($\geq 55\%$). The physical exergy reduction is mainly caused by the decrease of pressure of the produced water (Platform D) and of the exported oil (Platforms A, B and C) compared to the feed pressure.

The exergetic product mainly includes an exergy increase of the gas flows, either for injection (Platforms A and C) or for export (Platform B), with the exception of Platform D, where nearly 40 % of the exergetic product consists of the exergy increase of the seawater pumped for injection. Such conclusions may be expected, as the gas products mostly have significantly higher pressures than the feed streams. An exception is the exported gas from Platform B, which presents both lower pressure and temperature than the feed streams, but still displays a higher specific physical exergy than the feed streams.

Applying the same expression on a molar basis, returns different numerical values and conclusions (Table 6). Furthermore, the exergy fuels and products differ slightly for Platforms A, C and D, and significantly for Platform B. These inconsistencies are due to the different compositions of the feed and product streams that are compared. Different chemical components carry different amounts of physical exergy, and this is not taken into consideration. It is assumed that all components carry the same amount, either on mass or on molar basis. The calculations of the exergy fuels and products return different numerical values, depending on the basis used for comparison.

For instance, for Platform B, the specific physical exergy of the export gas stream is higher than of the feed streams, whilst the molar physical exergy is smaller. This is because the feed streams entering this platform have higher average molecular weights than the export gas stream (approximately 25 kg/kmol in the feed streams and 20 kg/kmol in the gas export). The specific and molar physical exergy of the inlet and outlet streams for Platform B are shown in Figure 9. The effects from this inconsistency may be small for distillation columns that separate components of similar weights and properties. However, these effects are considerable when considering oil and gas platforms, as some may process highly different chemical components.

By assuming that some details were not included in the presented approach [17,23,24] for the sake of simplicity, it is also possible to interpret that the physical exergy related to each chemical component in a feed stream should be compared to the physical exergy related to the same component in a product stream. In this interpretation, this approach will be similar to the one that will be presented in Section 5.
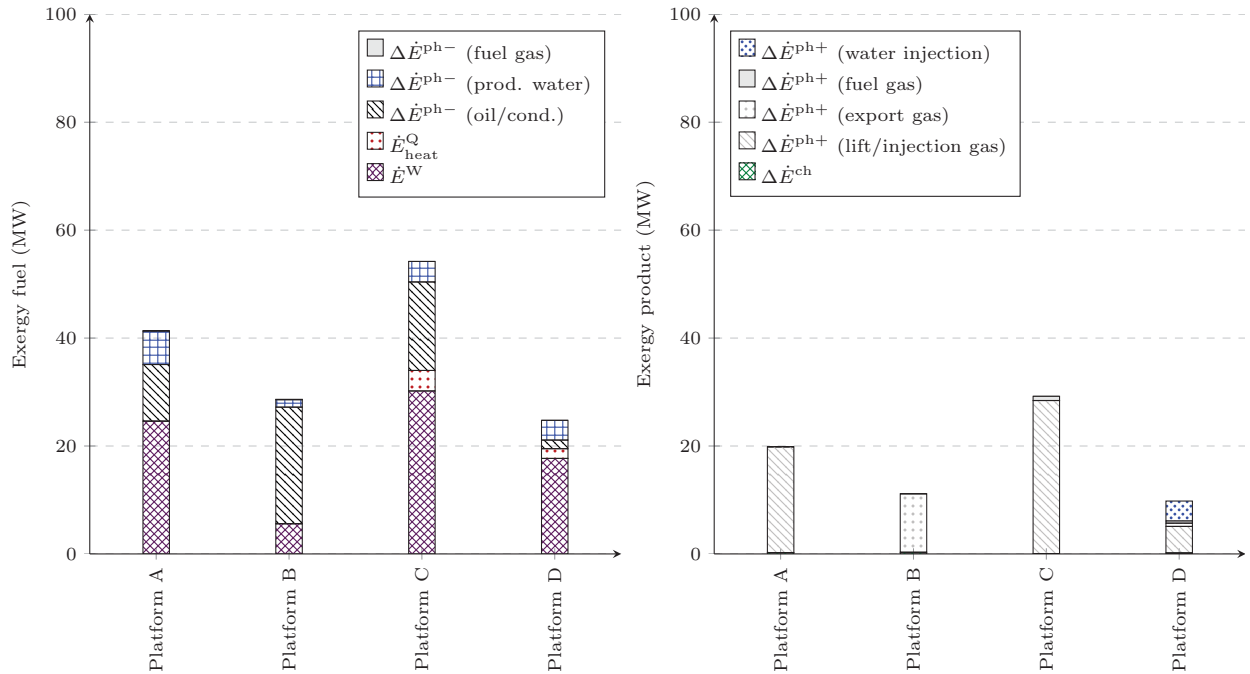

Figure 7: Exergy fuels and products, based on the approach of Tsatsaronis and Cziesla for distillation columns, calculated on a mass basis.
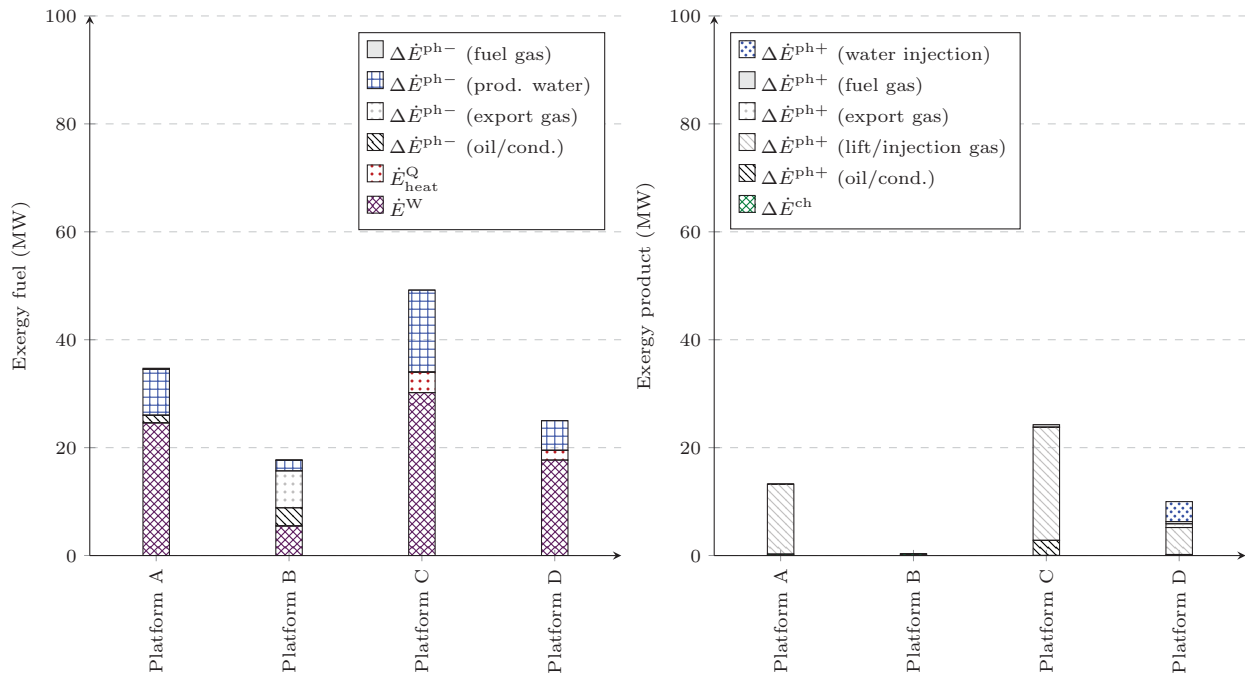
Figure 8: Exergy fuels and products, based on the approach of Tsatsaronis and Cziesla for distillation columns, calculated on a molar basis.
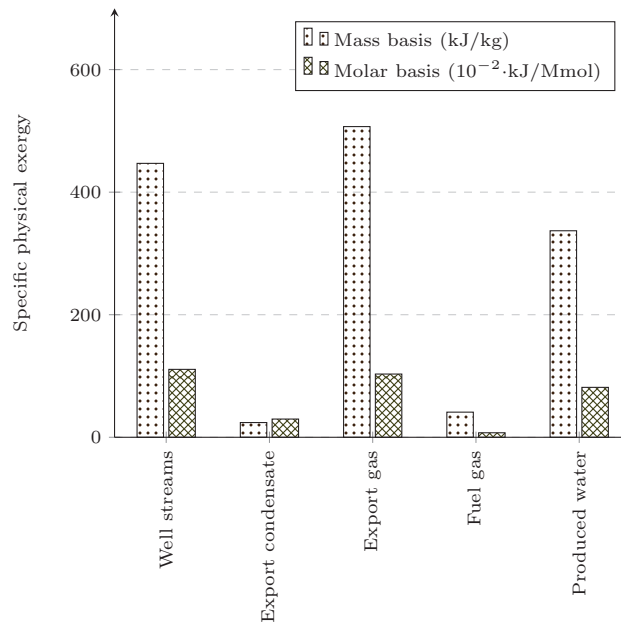

Figure 9: Specific physical exergy of the inlet and outlet streams for Platform B, expressed on a mass and molar basis.

4.6. Applicability to offshore processing plants

The calculations of exergy efficiencies with definitions found in the literature, and applied to our four offshore processing plants, raise several points of importance. The expressions were derived for either similar systems (e.g. the approach of Kotas [15] and Oliveira [28]) or systems that present common features to petroleum separation systems (e.g. the approach of Rian and Ertesvåg [30]). In consequence, they may not be fully applicable to the systems investigated in this work.

The *total* exergy efficiencies can unambiguously be calculated, but they can hardly be used for suggesting system improvements, as they do not assess the thermodynamic transformations taking place on-site. The *task* efficiencies reflect the tasks of the systems they are used for. The formulations presented so far show a few drawbacks and may favour or penalise platforms of a special type, or operating under certain conditions. The exergy efficiency as defined by Kotas [15], which was derived for oil and gas separation systems, fails for systems where the physical exergy outputs are smaller than the inputs (Platform B). The one suggested by Rian and Ertesvåg [30] is not directly applicable to oil and gas separation systems, as they investigate a gas facility where natural gas is cooled and liquefied. This refrigeration task is not found on any of the petroleum separation systems studied in this work. The literal formulation of an exergy efficiency as proposed by Tsatsaronis and Cziesla [16] has limitations, since the numerical values differ with the choice of a molar or mass basis. This approach may be applied at the level of each chemical component, to quantify precisely the exergy transfers taking place, rather than at the level of each material stream.

5. *Component-by-component* exergy efficiency

5.1. Concept

As seen in the previous section, the formulation of an exergy efficiency for oil and gas platforms is not straightforward, because of (i) the high transit chemical (and sometimes also physical) exergy of hydrocarbon components, (ii) the large variety of chemical components and (iii) the differences in process conditions and product specifications among these facilities. In order to fully evaluate the performance of a petroleum system and of separation processes, we propose the following formulation of exergetic efficiency. It builds on the same reasoning as presented in the work of Tsatsaronis and Cziesla [60]. The increase of chemical exergy between all input and output streams is taken as the first contribution to the exergetic product. The second contribution is related to increases in physical exergy of useful product streams. However, the specific physical exergies of the *entire* streams are not compared with the specific physical exergies of the feed streams. For each feed stream, different parts may end up in different products. Therefore, the physical exergy of each such part in the feeds are compared with the physical exergy of the corresponding parts in the products. This approach takes into account the fact that different chemical compounds carry different amounts of physical exergy. The exergy transfers are decomposed at the chemical compound level, rather than on the stream level. The exergy that is spent in the system is taken as the power and heat exergy consumed on-site, as well as the decrease of physical exergy of parts of streams that lose physical exergy on the way from feed to product. This is the same concept as that of the exergy efficiency that consider transit exergy [11], but carried out on the chemical component level.

A schematic overview of the component flows for a system with two components, two feeds and two products is shown in Figure 10. The physical exergy of each part at the outlet $\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}}$, will either have increased or decreased compared to the physical exergy of the same part at the inlet $\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}}$. Since the exergetic fuel and the exergetic product are evaluated at the chemical component level, this efficiency is called the *component-by-component* efficiency.

5.2. Derivation

The physical exergies of the *part* of a stream coming from feed j, $\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}}$, and ending up in product k, $\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}}$, are calculated using the following equations:

$$\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} = \sum_i \dot{n}_{i,j,k} \hat{e}^{\mathrm{ph}}_{i,j} \tag{22}$$
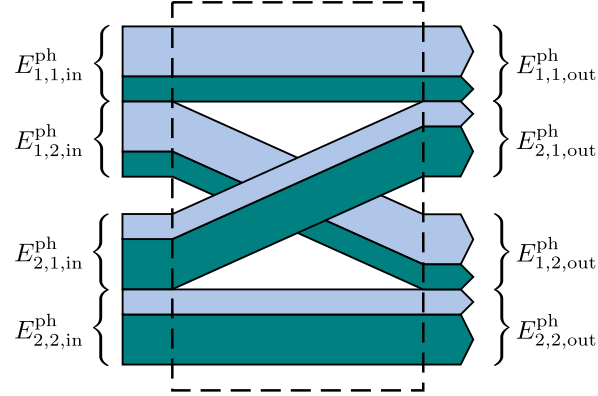
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Figure 10: Schematic overview of component flows in and out of a control volume for a system with two components marked with different colors, two feeds at the left and two product streams at the right.

$$\dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} = \sum_i \dot{n}_{i,j,k} \hat{e}^{\mathrm{ph}}_{i,k} \tag{23}$$

The symbol $\hat{e}^{\mathrm{ph}}_{i,j}$ denotes the partial molar physical exergy of component i in feed stream j, $\hat{e}^{\mathrm{ph}}_{i,k}$ denotes partial molar physical exergy of component i in product stream k and $n_{i,j,k}$ denotes the molar flow of component i from feed j to product k. The partial molar physical exergy of component i is defined as:

$$\hat{e}^{\mathrm{ph}}_i = \left(\frac{\partial E^{\mathrm{ph}}}{\partial n_i}\right)_{T,P,n_{l \neq i}} \tag{24}$$

and should not be confused with the molar physical exergy.

For each component in each feed stream, it is assumed that the fraction of the component ending up in each product stream is the same as the fraction of the total amount of this component entering as feeds ending up in each product stream. For instance, for methane in feed 1, it is assumed that the fraction of this methane ending up in product 1 is the same as the fraction of the total amount of methane ending up in product 1.

Physical exergy increases of parts of streams are denoted $\left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^+$ and can be expressed mathematically:

$$\left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^+ = \begin{cases} \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} - \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} & \text{if } \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} > \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} \\ 0 & \text{if } \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} < \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} \end{cases} \tag{25}$$

On the opposite, physical exergy decreases of parts of streams are denoted $\left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^-$ and can be expressed:

$$\left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^- = \begin{cases} 0 & \text{if } \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} > \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} \\ \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} - \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} & \text{if } \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{out}} < \dot{E}^{\mathrm{ph}}_{j,k,\mathrm{in}} \end{cases} \tag{26}$$

The exergy balance, Equation 13, can thus be rewritten:

$$\underbrace{\sum_j \sum_k \left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^- + \dot{E}^Q_{\mathrm{heat}} + \dot{E}^W}_{\dot{E}_{\mathrm{f}}} = \Delta \dot{E}^{\mathrm{ch}} + \underbrace{\sum_j \sum_{k,\mathrm{u}} \left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^+_{\mathrm{u}}}_{\dot{E}_{\mathrm{p}}} + \underbrace{\sum_j \sum_{k,\mathrm{w}} \left(\Delta \dot{E}^{\mathrm{ph}}_{j,k}\right)^+_{\mathrm{w}} + \dot{E}^Q_{\mathrm{cool}} + \underbrace{\dot{E}_{\mathrm{d,PP}}}_{\dot{E}_{\mathrm{d}}}}_{\dot{E}_{\mathrm{l}}} \tag{27}$$

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This result in the following expression for the exergy efficiency (ε_{II-4}):

$$\varepsilon_{II-4} = \frac{\sum_j \sum_k \left(\Delta \dot{E}_{j,k}^{\mathrm{ph}}\right)_{\mathrm{u}}^{+} + \Delta \dot{E}^{\mathrm{ch}}}{\sum_j \sum_k \left(\Delta \dot{E}_{j,k}^{\mathrm{ph}}\right)^{-} + \dot{E}_{\mathrm{heat}}^{Q} + \dot{E}^{W}}$$

$$= 1 - \frac{\sum_j \sum_k \left(\Delta \dot{E}_{j,k}^{\mathrm{ph}}\right)_{\mathrm{w}}^{+} + \dot{E}_{\mathrm{cool}}^{Q} + \dot{E}_{\mathrm{d,PP}}}{\sum_j \sum_k \left(\Delta \dot{E}_{j,k}^{\mathrm{ph}}\right)^{-} + \dot{E}_{\mathrm{heat}}^{Q} + \dot{E}^{W}} \tag{28}$$

This approach, at the chemical component level, takes into account the fact that in separation processes the feed and product streams display the same chemical components, but in different quantities. Gas mostly contains light hydrocarbons, which have much lower molecular weights than the hydrocarbons present in the oil. As different types of chemical components do not have the same thermodynamic properties (enthalpy and entropy) at the same environmental conditions (temperature and pressure), this implies that different components carry different quantities of physical exergy. Decomposing the physical exergy of a stream into the physical exergy per chemical component allows therefore for more accurate calculations of the exergy fuels and products. This splitting does not depend on whether a mass or molar basis is considered. The allocation of an exergy flow as an exergy product or fuel will depend solely on the partial physical exergy, which is a function of the temperature and pressure conditions, and not on whether the specific or molar exergy of the stream of interest is smaller or higher than of the feed stream.

This formulation of exergy efficiency is not valid only for oil and gas offshore platforms, but can be generalised to separation processes.

5.3. Results

The calculations of the exergy efficiency as given in Equation 28, suggest that Platforms D and C present the highest thermodynamic performances, while Platform B presents the poorest performance (Table 7). With the exception of Platform B, the major exergy fuel consists of the power consumed on-site to perform the pumping and compression operations (Figure 11).
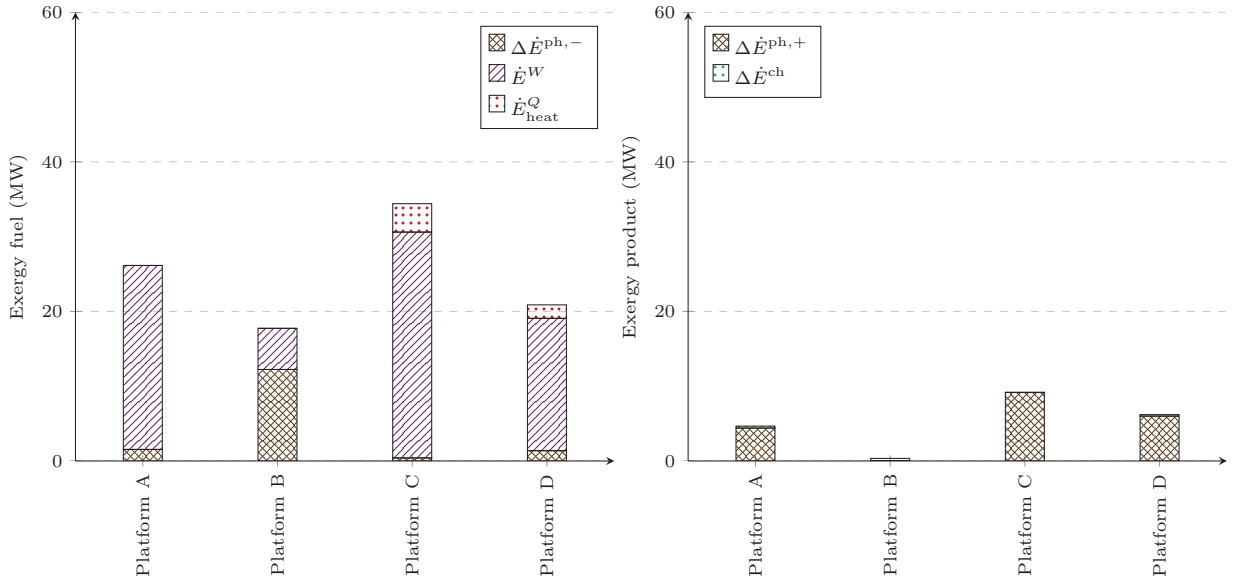

Figure 11: Exergy fuels and products, based on the *component-by-component* approach.

Table 7: *Task* exergy efficiencies (%) based on the *component-per-component* approach.

	Platform A	Platform B	Platform C	Platform D
ε_{II-4}	17.9	1.7	26.8	29.6

Oil and gas platforms perform separation, pumping and compression work, but in different magnitudes, and this explains some the large differences in terms of efficiencies between the four facilities:

- Platform A processes oil, gas and water: the three phases are separated, oil is pumped to another platform, gas is compressed to more than 200 bar for further injection, and water is discharged to the sea at low pressures. The *separation* work is small in comparison to the pumping work, and negligible towards the compression one.

- Platform B processes condensate, gas and water: gas and oil exported at a pressure lower than the feed pressure, and the separation work is mostly driven by the decreases in physical exergy.

- Platform C processes oil, gas and water: oil is exported at a much higher pressure than the feed pressure, and the pumping work on this platform is significantly higher than on Platforms A and B.

- Platform D processes oil, gas, and significant quantities of produced water. Seawater is pumped for further injection, and small quantities of gas are compressed and exported or injected compared to Platform A.

6. Discussion

6.1. Sensitivity

The problems that rise from the use of the total exergy efficiencies when evaluating petroleum separation processes stem from the fact that these expressions include the chemical exergy of hydrocarbons. The interest of these expressions of exergy efficiencies is limited, because these indicators return similar numerical values for all cases. They have so little sensitivity to changes in the system that they cannot be used for assessing the improvement potentials of oil and gas systems, or to analyse the different trade-off. All the *task* exergy efficiencies showed a clear difference between the four facilities, and are also expected to be sensitive to system improvements.

6.2. Feasibility and simplicity

The approaches found in the scientific literature presented all drawbacks compared to the *component-by-component* efficiency, stemming from the fact that they were derived for systems with partly different tasks. However, some of them require significantly less calculation efforts. The use of the exergy efficiencies as defined in the approaches of Kotas [15] and Oliveira [28], and of Cornelissen [26] and Rian and Ertesvåg [30], requires flow, temperature and pressure measurements, which are often already conducted, as well as crude oil and gas assays to estimate the composition. The *component-by-component* efficiency requires significantly more computational efforts than the other definitions, since the calculations are done on a component level, and the partial molar physical exergy of each component has to be calculated.

6.3. Transparency

The expressions and numerical values of the exergy efficiencies are dependent on the choice of the:

- environmental state: the environmental temperature has a direct impact on physical and chemical exergy, and the environmental pressure has an impact on the physical exergy;

- system boundaries: the inclusion of the import and export pipelines and of the gas lift system would impact the numerical values of the mechanical exergy increases.

The choice of the environmental state and the system boundaries should be made clear to allow for a sound comparison of different facilities.

6.4. Temperature-based and pressure-based exergy

The exergy balances and interpretation of product in the *component-by-component* efficiency can be improved by decomposing the physical exergy term into its temperature-based and pressure-based components. For example, one of the desired outcomes of the processing plant is the export of gas at high pressure, which is equivalent, from a thermodynamic viewpoint, to the production of pressure-based exergy. The temperature-based exergy of gas streams is a result of the turbomachinery component inefficiencies, and is dissipated to a large extent in the export pipelines. Pressure-based exergy increases should therefore be accounted as a part of the exergetic product (desired outcome of the system), while the temperature-based exergy increases should be considered as a part of the exergetic losses. These considerations were also emphasised in the studies of Kotas [15], Cornelissen [26] for oil and gas distillation systems, and Marmolejo-Correa and Gundersen [61] for LNG processes.

Such decompositions would further increase the required computational efforts [23,24]. In the present cases, it is expected that the decomposition would only very slightly affect the numerical results, as the pressure-based exergy of gas generally dominates the temperature-based exergy (96 % against 4 % in the work of Voldsund et al. [41] for Platform A). The benefit of such an improvements in the efficiency should be evaluated against the larger required computational efforts.

6.5. Theoretical versus practical improvement potential

Exergy efficiencies should give hints for setting meaningful benchmarks and evaluate unambiguously the performance of the system under study. They should provide a measure of the resources that are required to drive the processing plant and platform, and of the desired outcome of these systems. One may argue that these targets are not realistic, as there are practical constraints:

- economical – integrating other components or redesigning the system may be costly, and possibly cause shut-downs of the plant during the installation phase;

- technical – the structural design of the processing plant is partly fixed and bound by the field characteristics (e.g. temperatures and pressures) and the export conditions (e.g. purity);

- technological – the performance of a process component is limited by the current technological advances (e.g. state-of-the art centrifugal compressors).

This implies that only a part of the thermodynamic inefficiencies taking place in petroleum separation processes can be reduced in practice, whereas another part cannot be avoided.

Bejan et al. [21] emphasised the difficulty of using the exergy efficiency for comparing systems with dissimilar functions, which is the case of oil and gas platforms. All platforms have the functions of separation, compression and pumping, but due to differences in their operating conditions (field conditions and product specifications), some platforms must achieve more compression work (Platform A), others mainly perform pumping work (Platform D), and some may do less of compression and pumping, and thus almost only separation (Platform B). In general, pumps are characterised by a higher exergetic performance than compressors, and the latter are more exergy-efficient than systems with separation tasks. Different systems present therefore different potentials for improvement.

One way to overcome this problem may be to evaluate different sub-processes separately. If for instance the performance of separation was evaluated individually, or similarly the performance of compression or pumping, the platforms could be compared on a similar basis. The issue of comparing systems with dissimilar functions would be eliminated.

Another way to tackle this is to define an additional performance indicator that evaluates the performance related to what is practically achievable. The following reasonings may be applied:

- Tsatsaronis and Park [60], who defined the unavoidable exergy destruction as the exergy that is destroyed when the current components are operated at their maximum efficiency, considering technological limitations that could not be overcome in the near future, regardless of the investment costs;

- Margarone et al. [62], who proposed to compare the current plant performance against that obtainable when integrating the state-of-the-art technologies present on the market;

- Johannessen et al. [63,64], who suggested to set a state of minimum entropy production or minimum exergy destruction for a given operation target, and the difference between the current value and this minimum would be considered as an excess loss.

Such approaches could both give a more realistic target for each platform, and allow for comparison on how well they utilise their practically achievable potential. The main criticisms against these approaches are the degree of subjectivity when defining the state of unavoidable exergy destruction, and the high sensitivity of such targets to future technological achievements.

6.6. Performance and ageing

It is generally admitted that the performance of oil and gas platforms decreases with time, as a result of ageing and degradation of the on-site components and processes. Meanwhile, the main function of an offshore platform may change over time due to changing operating conditions. For instance, an increased gas-to-oil ratio for Platform A resulted in more necessary compression work over the last 20 years, while increased water-to-oil ratio for Platform D has resulted in more pumping work necessary. The *component-by-component* efficiency can then show results that are biased by the change in the relative importance of compression, pumping and separation over time. It evaluates correctly the utilisation of the theoretical potential, i.e. the distance from a reversible process. However, in order to see a decrease in performance, as it could be expected, approaches such as the ones mentioned in Section 6.5 may be preferable. They evaluate the utilisation of the potential that is achievable with today's technologies, and not the potential that is reachable if the process was reversible. Such issue may not be faced in the case of other petrochemical processes, since the variations over time of the gas and water contents of the feed are not as significant.

6.7. Significance

Exergy efficiency indicators may be coupled to other performance criteria, such as the specific power or exergy consumptions, which assess the expense of resources for a given unit of oil and gas. The latter illustrate different aspects of the current operations. For instance, taking the *component-by-component* efficiency, one can conclude that Platform B presents the smallest exergy efficiency of the four investigated cases. It should be noticed that this facility has also the smallest specific power consumption, because there is very little need for compression. This characteristic illustrates the effects of the field conditions and export specifications on the system performance.

6.8. Generalisation

The *component-by-component* efficiency presented in this paper may be of interest for petrochemical systems other than oil and gas platforms. It can be applied to industrial systems where petroleum is fractionated, since similar processes take place (compression, expansion, separation, distillation).

Some of the major differences are:

- the much greater amount of heat exergy consumed in some separation process, as large quantities of heat are required to preheat oil and to sustain the temperature gradient of distillation columns [3]. Separation of the oil fractions in refineries is therefore more temperature-driven than pressure-driven, at the difference of oil and gas platforms.

- the quantity of exergy destroyed in distillation columns in refineries represents a non-negligible part of the total exergy input, at the difference of oil and gas platforms where it represents less than 3 % in any of the studied cases.

Although oil and gas platforms and oil refineries aim at separating the hydrocarbons composing the oil and gas mixtures, the performance of both systems may not be directly comparable since the structural design setup are fundamentally different.

7. Conclusion

Exergy efficiency definitions found in the scientific literature for similar systems had drawbacks such as (i) low sensitivity to efficiency improvements, (ii) calculation inconsistencies or (iii) favoured facilities with certain boundary conditions when applied to the four offshore processing plants. Based on these experiences, the *component-by-component* efficiency was proposed. This efficiency is sensitive to process improvements, gives consistent results and evaluates successfully the theoretical improvement potential. However, it requires high computational efforts. It ranges between 1.7 and 29.6 % for our four cases. This efficiency is also applicable to other petroleum processes.

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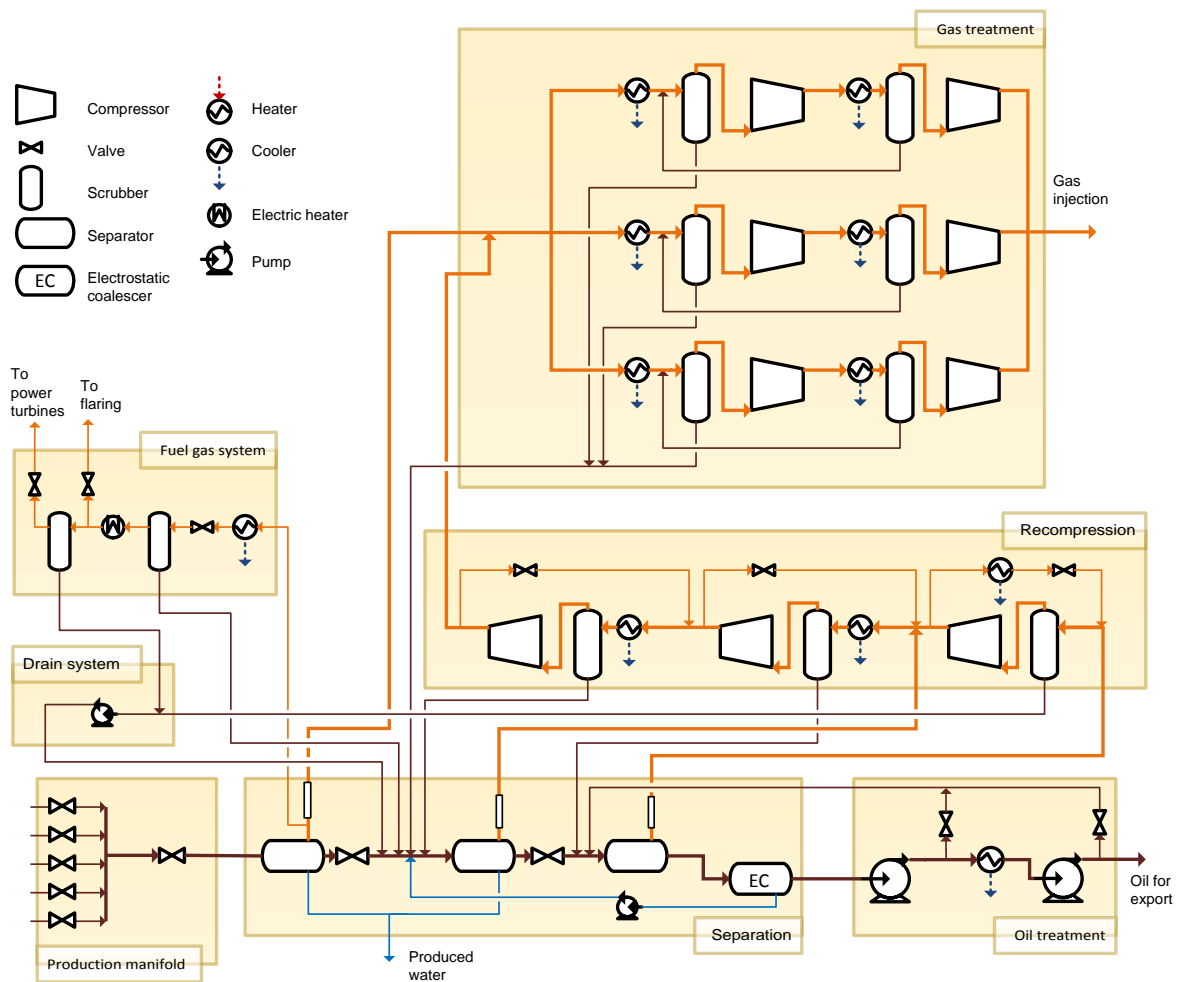## Appendix A. Process flow diagrams

Figure A.12: Process flow diagram of the processing plant of Platform A. Gas streams are shown with orange arrows, water streams with blue arrows, and oil, condensate and mixed streams are shown with brown arrows.
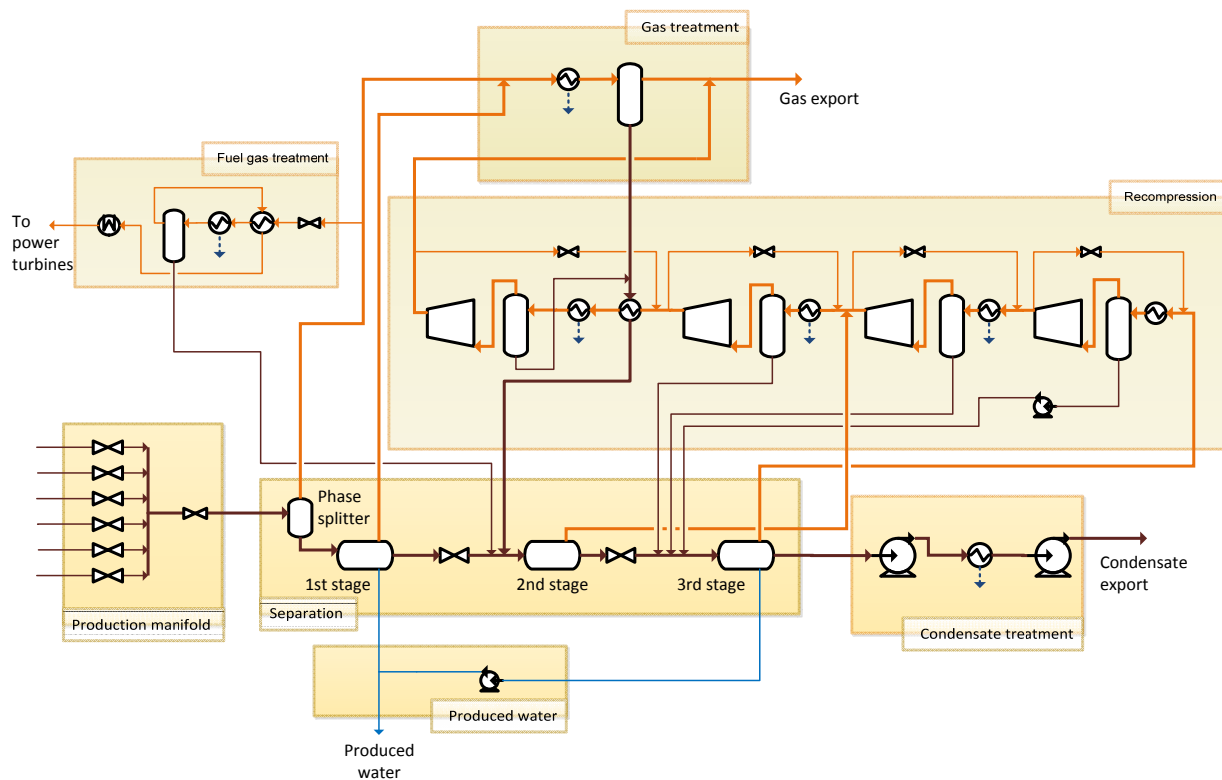
Figure A.13: Process flow diagram of the processing plant of Platform B. Gas streams are shown with orange arrows, water streams with blue arrows, and oil, condensate and mixed streams are shown with brown arrows. Symbol explanations can be found in Fig. A.12
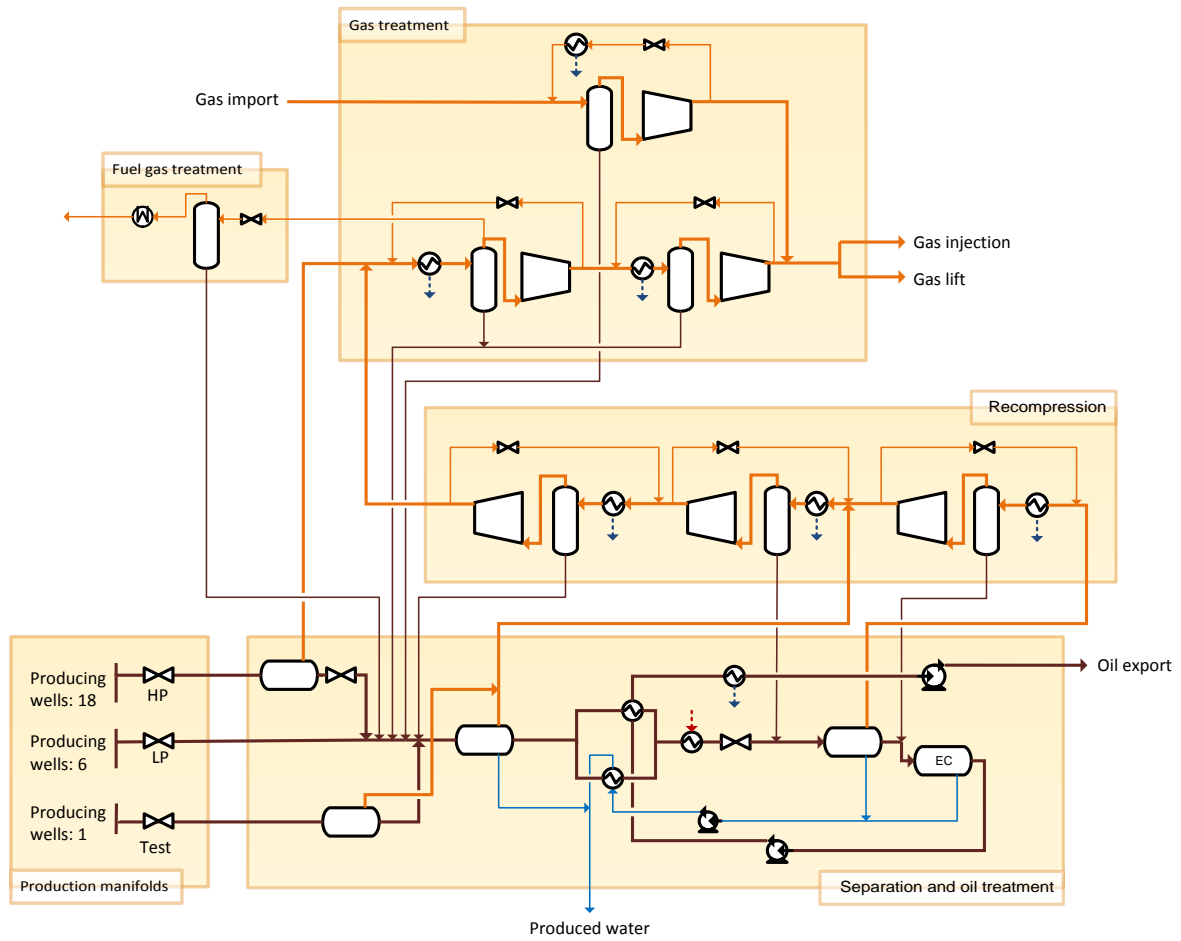
Figure A.14: Process flow diagram of the processing plant of Platform C. Gas streams are shown with orange arrows, water streams with blue arrows, and oil, condensate and mixed streams are shown with brown arrows. Symbol explanations can be found in Fig. A.12
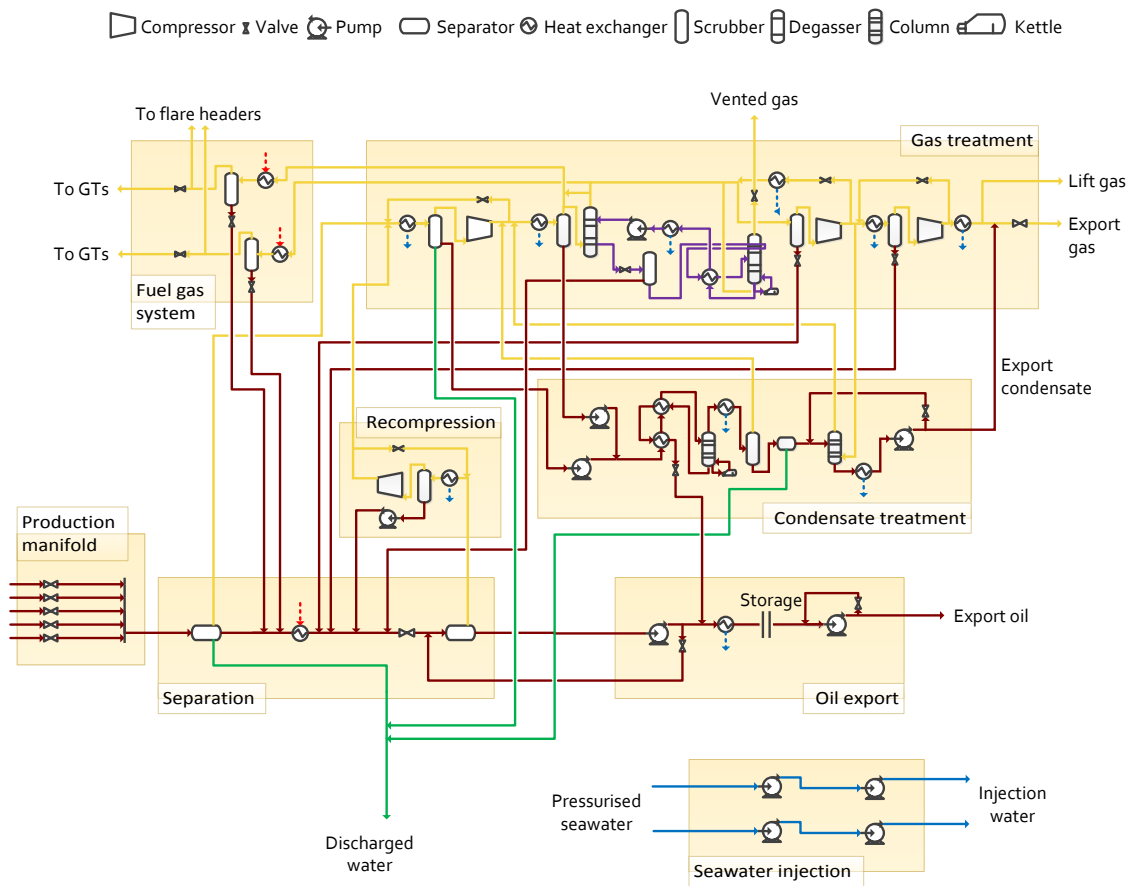
Figure A.15: Process flow diagram of the processing plant of Platform D. Gas streams are shown with orange arrows, water streams with blue arrows, glycol is shown with purple arrows, and oil, condensate and mixed streams are shown with brown arrows.