Assessment of the exergy performance of a floating, production, storage and offloading (FPSO) unit: Influence of three operational modes

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Abstract:

Oil and gas industries are developing energy efficiency programs in order to enhance the performance of their production activities, including the floating, production, storage and offloading (FPSO) operations. FPSOs are floating vessels designed for hydrocarbons processing and include other functions such as: oil treatment and storage, gas treatment and compression for export, lift, and injection, and seawater treatment and injection. The exergy method is useful to identify potential energy savings for the improvement of the FPSO processes. In this study, an evaluation of the exergy performance of the FPSO is carried out and the main goal is to investigate the influence of three operating modes on the following criteria: exergy efficiency, specific exergy consumption, renewability exergy index, CO_2 emissions and CO_2 emissions normalized to exergy of the product streams of the plant. The FPSO performance assessment described in this paper takes into account three operational modes depending on the CO_2 content in the well stream. Additionally, the FPSO utilizes membrane technology for CO_2 removal from the separated gas. In the operational mode 1, all gas is sent through the bypass of the CO_2 removal system and it is injected into the production wells; in the mode 2, part of the gas is treated in the CO_2 removal system to be exported, and the other part is injected in the production wells; and in the mode 3, all gas is exported and the removed CO_2 is injected in the well. Simulations of the processing and utilities plants in the FPSO were carried out using software Aspen HYSYS®. Results show that the observed variations in exergy efficiency of the three operational modes could be, mainly, attributed to the increase of oil and gas fractions in the well stream.

Keywords:

Exergy performance; FPSO; Exergy efficiency; Operational mode; CO_2 emissions

1. Introduction

Oil and gas industry requires energy savings in order to improve their operations. The implementation of energy management systems in accordance with ISO 50001 is an important framework to develop better practices in technical and environmental levels. Different energy performance indicators have been established in order to assess the resources consumption and, consequently, to explore strategies to improve the energy performance of oil and gas facilities [1]. These indicators are based on the First Law of Thermodynamic but is important to considerate the quality of resources by means of performance indicators based on the Second Law of Thermodynamic.

In oil and gas industry, FPSOs are offshore installations used to perform operations of production of petroleum. An advantage of FPSOs is their storage capacity for the treated crude oil produced as well as the possibility to operate in remote areas. A FPSO incorporates all equipment related to a fixed installation in its processing and utilities plants [2].

According with literature, the first exergy study applied to an offshore installation was developed by Oliveira and Van Hombeeck [3]. They performed an exergy analysis of petroleum separation processes of a typical Brazilian offshore platform. This study concluded that heating operations that precede the separation of petroleum are important consumers of the exergy resource of the plant. In recent years, there has been an increasing amount of literature on the exergy analysis applied to offshore industry. Nguyen et al [4] carried out a thermodynamic analysis of the processing plant in an offshore platform operated on a mature field. The results of this study indicated that the gas treatment is the main exergy destruction process followed by the recompression process and the production manifold process. Nguyen et al [5] developed a study about the definition of exergy efficiencies applied to offshore oil and gas processing. The application of the exergy definitions found in the literature to four offshore processing plants showed that there are some drawbacks such as low sensitivity to efficiency improvements and calculation inconsistences. Nguyen et al [6] applied exergy accounting in order to compare the performance of an offshore platform in three stages of the oil field (early-life, plateau and end-life productions). They founded that the exergy destruction changes considerably with time, which is associated with the variability of oil production and the water extraction. Nguyen et al [7] studied the exergy performance of energy systems on North Sea oil and gas platforms. They investigated six simulation cases to analyse the influence of reservoir fluid composition. Among their conclusions, it was reported that exergy destruction is distributed about 65% for utilities plant and 35% for processing plant. Voldsund et al [8] conducted a study related to the exergy destruction and losses on four offshore platforms. Their comparison found large exergy destruction associated with the gas treatment process followed by the process in the production manifold systems. Voldsund et al [9,10] performed an exergy analysis on oil and gas processing on a North Sea oil platform a real production day. It was concluded that processes that increase pressure (compressors) and processes that decrease pressure (reduction valves) are responsible for most exergy destruction. Voldsund et al [11] investigated about some exergy indicators and its applications to four oil and gas platforms. Among others, their work concluded that exergy efficiency results depend on the interpretation of product exergy and utilized exergy. Carranza and Oliveira [12] developed an exergy analysis of a petroleum offshore platform process plant with CO_2. This study found that the implementation of a CO_2 capture system reduces the CO_2 emissions in 75% which is environmentally beneficial; on the contrary, the exergy efficiency is reduced in 2.7 points. Carranza and Oliveira [13] carried out a detailed exergy assessment on the components of the oil and gas offshore platform presented in [12]. This work concluded that separation train heaters are the components with the highest exergy destruction.

This paper presents the results of the exergy and environmental analysis of energy conversion processes that take place in the utilities and processing plants of a FPSO. The aim of this work is to assess the exergy performance of a FPSO offshore facility considering the influence of its operational modes. Three operational modes have been studied in order to assess the exergy performance by means of the exergy efficiency and the specific exergy consumption criteria, and the environmental performance by means of the renewability exergy index, the CO_2 emissions and the CO_2 emissions normalized to exergy of the product streams of the FPSO. The remainder of this paper is divided into four sections. The second section describes the theoretical background used to calculate some thermodynamic variables and the thermodynamic performance. In the third, a description of the FPSO systems, the operational modes, and simulation details is presented. Comparative results and discussion of the exergy performance of the FPSO are presented in the fourth section, and finally, the fifth section presents the conclusions of the work.

2. Theoretical background

Exergy flow rate $\dot{B}$ can be calculated by the following general equation in which four components are considered: kinetic exergy (k), potential exergy (p), physical exergy (ph), and chemical exergy (ch):

$$\dot{B} = \dot{B}_k + \dot{B}_p + \dot{B}_{ph} + \dot{B}_{ch}. \qquad (1)$$

In this work, kinetic and potential components of exergy streams are not considered. Specific physical exergy may be determined by:

$$b_{ph} = (h - h_0) - T_0(s - s_0), \qquad (2)$$

where h is the specific enthalpy, s is the specific entropy and the subscript 0 is referred to the restricted dead state, which is defined by T_0 and p_0. Specific enthalpy and entropy calculations have been obtained from Aspen HYSYS® [14]. Chemical exergy is the maximum work that can be obtained when a system goes from the restricted dead state to the dead state [15]. The specific chemical exergy of a mixture per mole of the gas mixture is given by:

$$b_{ch} = \sum_i x_i b_{ch}^i + \bar{R}T_0 \sum_i x_i \ln\gamma_i x_i, \qquad (3)$$

where x_i is the mole fraction of the i-th component in the mixture, b_{ch}^i is the chemical exergy of the i-th component, and γ_i is the activity coefficient of the i-th component, and it is taken as 1 for petroleum components [16,17]. Calculation details of the chemical exergy for components and pseudo-components of petroleum are described in [12]. According to [18], in processes that do not involve chemical reactions, there are no changes in chemical composition of streams, and if there is no exchange of substances with the environment, the chemical component of exergy will cancel out when exergy of the incoming and outgoing streams are subtracted in an exergy balance. Hence the exergy flow rate variations may be calculated by the following equation:

$$\sum_i \dot{B}_i = \sum_i [\dot{m}_i (h - T_0 s)_i]. \qquad (4)$$

The previous equation has been used in calculations of the global separation process in the FPSO. This calculation methodology reduces some complications associated with chemical exergy calculation of petroleum components. The exergy balance for a control volume operating in steady state permits to express the destroyed exergy $\dot{B}_d$ as [18]:

$$\dot{B}_d = \sum_{in} \dot{B}_i - \sum_{out} \dot{B}_i + \sum \dot{B}^Q - \dot{W}, \qquad (5)$$

where $\sum_{in} \dot{B}_i$ and $\sum_{out} \dot{B}_i$ are the sum of the inlet and outlet exergy flow rates, respectively, $\sum \dot{B}^Q$ is the sum of thermal exergies, and $\dot{W}$ is the power in the cv.

In this work, three exergy criteria have been used to assess the performance of the FPSO. An additional criterion used to evaluate the environmental performance of the FPSO is the carbon dioxide emission. The first criterion is the *exergy efficiency* η_B [18,19]. It measures the ratio between the exergy flow rate output and the exergy inlet rate, see (6). Exergy flow rate output or exergy product consists in the variation between the exergy content of the separated products $\dot{B}_P$ (gas, oil and water) and the exergy content of the mixture $\dot{B}_M$ (crude oil and dilution water). The exergy inlet rate is given by the exergy flow rate $\dot{B}_U$ used to provide the exergy flow rate output. In this study, the utilized exergy $\dot{B}_U$ is the exergy content of the fuel used to satisfy the energy requirements of the processes in the FPSO.

$$\eta_B = \frac{\sum \dot{B}_P - \dot{B}_M}{\dot{B}_U}. \qquad (6)$$

The second criterion is the *specific exergy consumption* SEC, which was expressed by Voldsund et al. [11] as the exergy consumption per standard volume oil equivalent exported. For the FPSO, this exergy-based indicator may be written as the ratio between the exergy consumption and the equivalent volumetric flow rate of oil processed:

$$SEC_{volume} = \frac{\dot{B}_U}{\dot{V}_{processed}}. \qquad (7)$$

Specific exergy consumption takes into account the quality levels of resources or products and it is useful to complement some energy performance indicators based on the First Law of the Thermodynamic which are used in oil and gas industry [1].

The third criterion is the *renewability exergy index* λ [19]. This index is used to evaluate renewability of energy conversion processes and it is calculated by means of (8). The renewability exergy index measures the ratio between the exergy associated with the useful product of the process B_{prod} and the sum of the exergy associated to the fossil fuels required B_{fossil}, the destroyed exergy B_{dest}, the needed exergy to deactivate the wastes B_{deact}, the exergy related to waste disposal B_{disp}, and the exergy of wastes that are not treated or deactivated B_{emis}.

$$\lambda = \frac{\sum B_{prod}}{B_{fossil} + B_{dest} + B_{deact} + B_{disp} + \sum B_{emis}}. \qquad (8)$$

Depending on the value of the renewability exergy index, it indicates that:

- Processes with $0 \leq \lambda < 1$ are environmentally unfavorable.
- For internal and externally reversible processes with non-renewable inputs, $\lambda = 1$.
- If $\lambda > 1$, the process is environmentally favorable, and additionally, increasing λ implies that the process is more environmentally friendly.
- When $\lambda \rightarrow \infty$, it means that the process is reversible with renewable inputs and no wastes are generated.

International Association of Oil & Gas Producers (OGP) has compiled environmental data from its members in order to compare their performance with other companies. Gaseous emissions constitute one of the six environmental indicator categories used to assess the performance of oil and gas industry. Carbon dioxide is the first of the gaseous emissions considered most important from regulatory perspectives [20]. In this work, emissions of CO_2 and CO_2 emissions normalized to exergy of the product streams are the fourth and the fifth criterion, respectively, used to evaluate the environmental performance of the FPSO. CO_2 emissions are directly obtained from the simulation performed in Aspen HYSYS®.

3. System description and simulation

Figure 1 shows a typical layout of the process modules in a FPSO. Configurations studied in this work are in accordance with typical plant requirements of the FPSOs installations in pre-salt areas in Brazil. The simulated FPSO is constituted by a processing plant and a utilities plant. Fig. 2 shows a simplified scheme of the FPSO processes studied in this work. In the processing plant, the separation train has been modelled with three separation stages. A three-phase separator is used in the first separation stage meanwhile the oil pre-heating and oil heating processes are installed between the first and the second separation stages. The second separation stage has been modelled as a two-phase separator with a three-phase separator. This last substitutes the electrostatic treatment in the real process. The third separation stage is modelled by means of a three-phase separator. The gas from second and third separation stages is compressed in the vapour recovery unit and sent to the main compressors. Separated oil is recirculated to preheat the oil from the first separation stage, and thereafter the recirculated oil must be cooled to 60 °C.

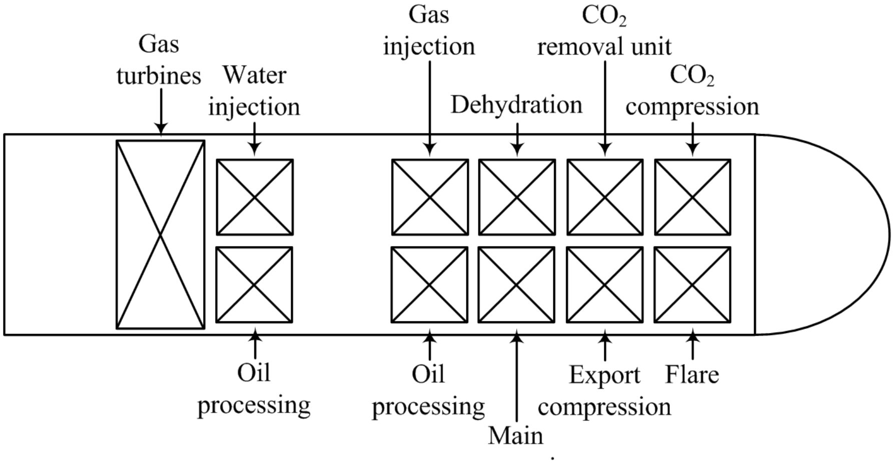

Fig. 1. Typical FPSO topside configuration.

Produced gas in the FPSO must be collected, treated and compressed to be used for: pipeline transportation, injection into reservoir to recovery operations, gas-lift, and fuel. The processes of the gas natural treatment in the FPSO are: 1) Main compression, 2) Gas dehydration, 3) CO_2 removal by means of membranes, 4) Natural gas side, in which two processes can be performed: 4a- Export gas compression and 4b-Combined compression with injection of natural gas, 5) CO_2 removed side, in which two processes can be carried out: a-CO_2 compression and b-Combined compression with injection of CO_2.

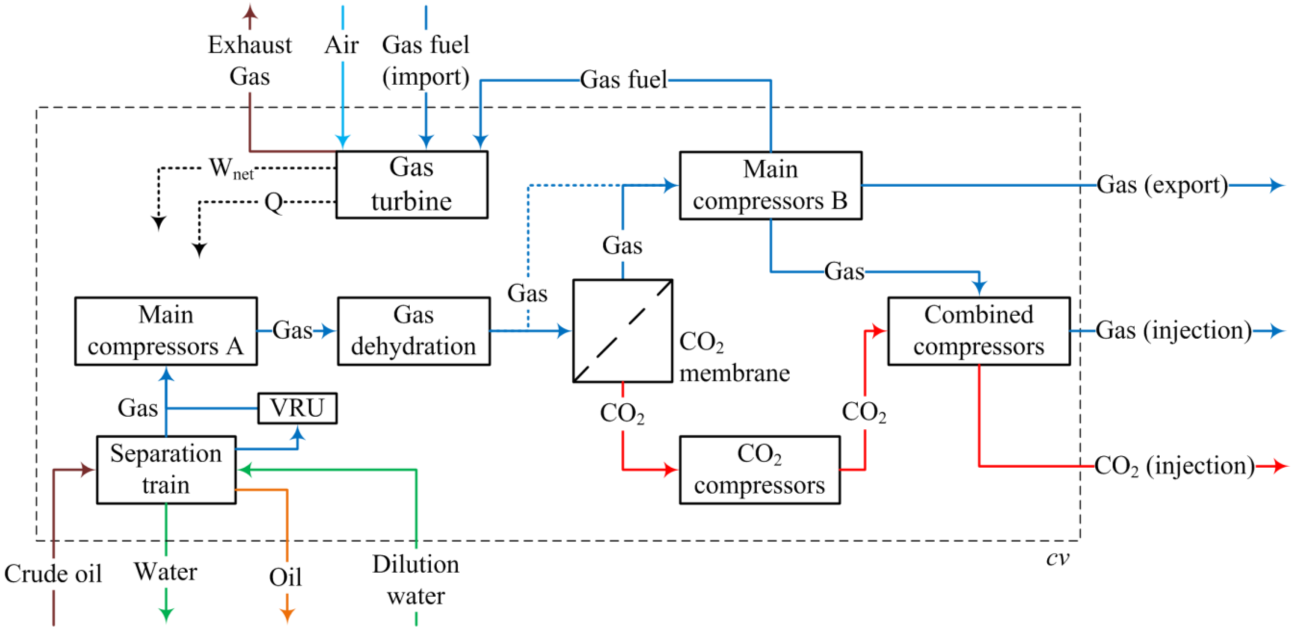

Fig. 2. Simplified scheme of the FPSO processes.

The produced gas in the separation train is compressed in the first compression train (main compressors A, Fig. 2) and then it is treated in the gas dehydration system by means of molecular sieves. Dehydrated gas is then sent to the CO_2 removal process or it may be by-passed when all or part of gas must be injected. Main compressors B can be used to increase the gas pressure for three operational alternatives: gas exportation, gas fuel, and gas injection. Combined compressors are used to increase the pressure for gas and CO_2 injection processes. The CO_2 separated in the membrane is compressed in the CO_2 compression train and in the combined compression train in order to be injected. Injection of gas and CO_2 in the wells is useful to enhance the recovery operation. Imported gas fuel is only necessary when all gas is injected in the wells.

The following are some general considerations regarding the modelling and simulation in this work:

- Three operational modes were analyzed considering the same mass flow, temperature and pressure of crude oil.
- The references temperature and pressure are, respectively, T_0=298.15 K and p_0=101.325 kPa.
- Crude oil desalting process was not considered but dilution water was used in the model (0.8% of dilution water for mode 1, 2% for the mode 2 and 4% for the mode 4).
- Electrostatic treatment of oil was not considered in order to simplify the simulation.
- Injection of water in wells, gas-lift and flare processes were not considered due to insufficient operating data.
- H_2S treatment unit is not considered because crude compositions do not include sulfur.
- Anti-surge control system of compressors was not considered.
- The efficiency of the process of CO_2 removal by membranes is assumed as 100%.
- It is assumed a complete removal of water in the gas dehydration system.
- Gas temperatures in the discharge of all compressors have been adjusted in order to prevent gas condensation.

Table 1 shows the composition of the crude oil for the three operational modes studied in this paper. According with the typical operational data of pre-salt areas in Brazil, the mode 1 composition corresponds to the maximum quantity of water/CO_2 into the crude oil, the mode 2 composition is referred to basic sediment and water (BSW) about 50%, and the mode 3 composition is for the maximum quantity of oil/gas. The gas-to-oil ratio (GOR) of the reservoir fluid is 461 sm^3/stm^3 for mode 1, 183 sm^3/stm^3 for mode 2, and 252 sm^3/stm^3 for mode 3.

Table 1. Crude oil composition of the three operational modes (molar fraction)

Component	Mode 1 (maximum water/CO_2)	Mode 2 (50% BSW)	Mode 3 (maximum oil/gas)	Component	Mode 1 (maximum water/CO_2)	Mode 2 (50% BSW)	Mode 3 (maximum oil/gas)
Methane	0.0291	0.0712	0.5928	Propane	0.0020	0.0066	0.0478
H_2O	0.8977	0.8393	0.0370	Ethane	0.0033	0.0086	0.0704
C20+*	0.0041	0.0120	0.0575	Oxygen	0.0000	0.0000	0.0000
n-C11	0.0006	0.0022	0.0100	Nitrogen	0.0002	0.0008	0.0037
n-Decane	0.0007	0.0026	0.0123	n-C19	0.0002	0.0010	0.0043
n-Nonane	0.0008	0.0027	0.0135	n-C18	0.0003	0.0011	0.0049
n-Octane	0.0009	0.0032	0.0165	n-C17	0.0003	0.0011	0.0048
n-Heptane	0.0007	0.0028	0.0114	n-C16	0.0003	0.0013	0.0053
n-Hexane	0.0006	0.0006	0.0112	n-C15	0.0004	0.0016	0.0069
n-Pentane	0.0007	0.0014	0.0085	n-C14	0.0004	0.0018	0.0074
i-Pentane	0.0002	0.0007	0.0055	n-C13	0.0005	0.0020	0.0087
n-Butane	0.0008	0.0023	0.0183	n-C12	0.0005	0.0019	0.0091
i-Butane	0.0003	0.0012	0.0093	CO_2	0.0544	0.0301	0.0229

3.1. Operational mode 1

This operational mode is utilized when the crude oil has the maximum quantity of water/CO_2. All separated gas is sent through the bypass of the CO_2 removal system and it is injected into the production wells. Fig. 3 shows the operational scheme of the FPSO in the mode 1. Crude oil is separated into gas, oil and water, and the pressure of the separation train varies from 23 bar to 2.3 bar approximately. Oil is treated to obtain the specified conditions of the process and the recovered vapour is compressed and transferred to the main compressor A. Oil heating process in the separation train is made using 130 °C hot water obtained from a heat recovery unit that uses the exergy from the gas turbine exhaust gases. In the main compression train A, the gas pressure is increased until 79 bar and it is sent to the dehydration unit in order to reduce the moisture content. By-passed gas is then compressed to 250 bar in the main compressor B section and, finally, it is compressed to 494 bar in the combined compressors section to be injected. In this operational mode gas is imported to be used as fuel in the gas turbine. Imported gas has the following molar composition: methane 75.67%, ethane 10.97%, propane 6.65%, CO_2 3.00%, n-butane 1.55%, among others.

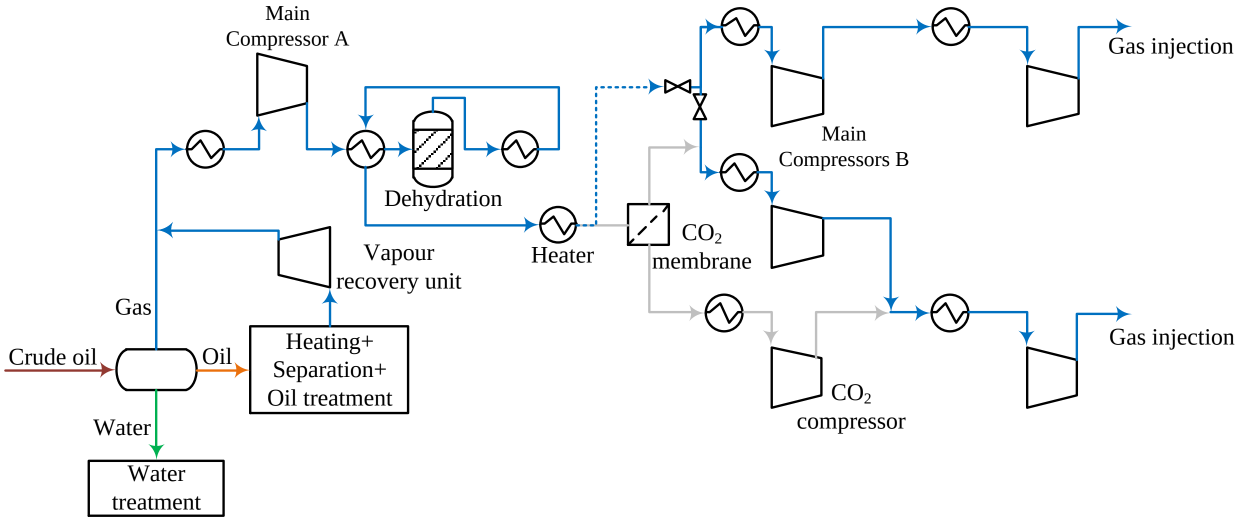

Fig. 3. Simplified scheme of the operational mode 1.

3.2. Operational mode 2

Operational mode 2 is applied when the crude oil has a BSW about 50% which permits gas exportation possibilities. In this operational mode, part of the gas is treated in the CO_2 removal unit in order to be exported and the by-passed gas is injected in the production wells. It was assumed that 50% of the gas from the separation train is treated for exportation purposes and 50% is treated to be injected. Separated CO_2 is also injected into the wells at 494 bar. Fig. 4 presents the operational scheme of the FPSO in the mode 2. Gas exportation process is carried out to 250 bar and other pressure conditions are similar to the mode 1. Fuel gas for the gas turbine is taken from the outlet of the CO_2 removal process and it is composed principally by: methane 79.28%, ethane 9.52%, propane 6.74%, n-butane 1.69%.

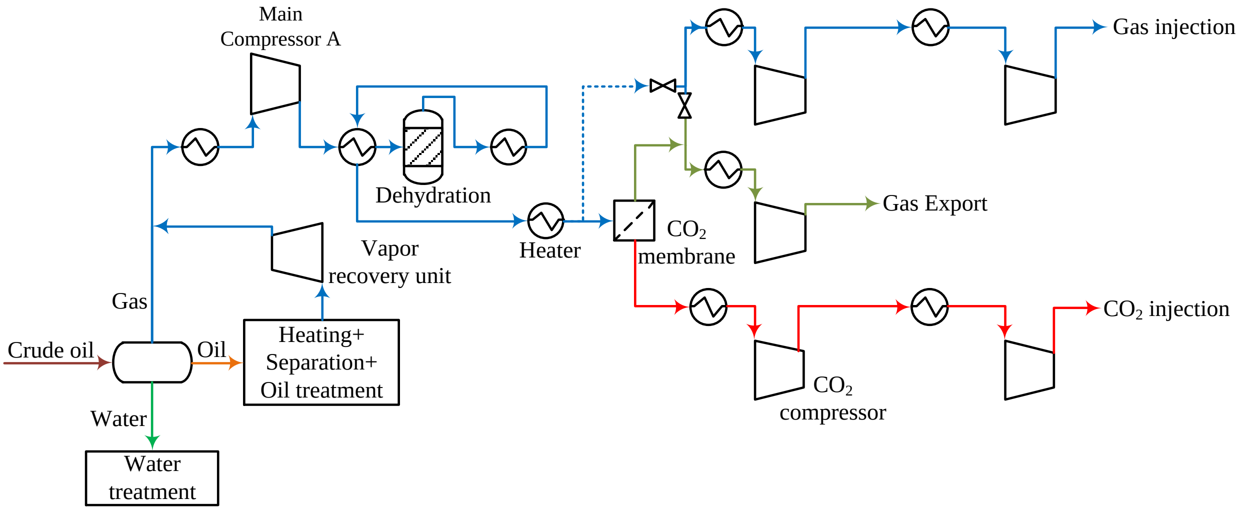

Fig. 4. Simplified scheme of the operational mode 2.

3.3. Operational mode 3

This operational mode is implemented when the crude oil has the maximum content of oil/gas. This aspect indicates a viability to remove the CO_2 from the gas for its exportation. All gas is exported and the removed CO_2 is injected in the well. Fig. 5 shows the operational scheme of the FPSO in the mode 3. Pressure conditions are similar to the previous modes. In this operational mode, the fuel gas is obtained from the treated gas after the CO_2 membrane unit. Its molar composition is given mainly by: methane 80.63%, ethane 9.51%, propane 6.10%, n-butane 1.72%.

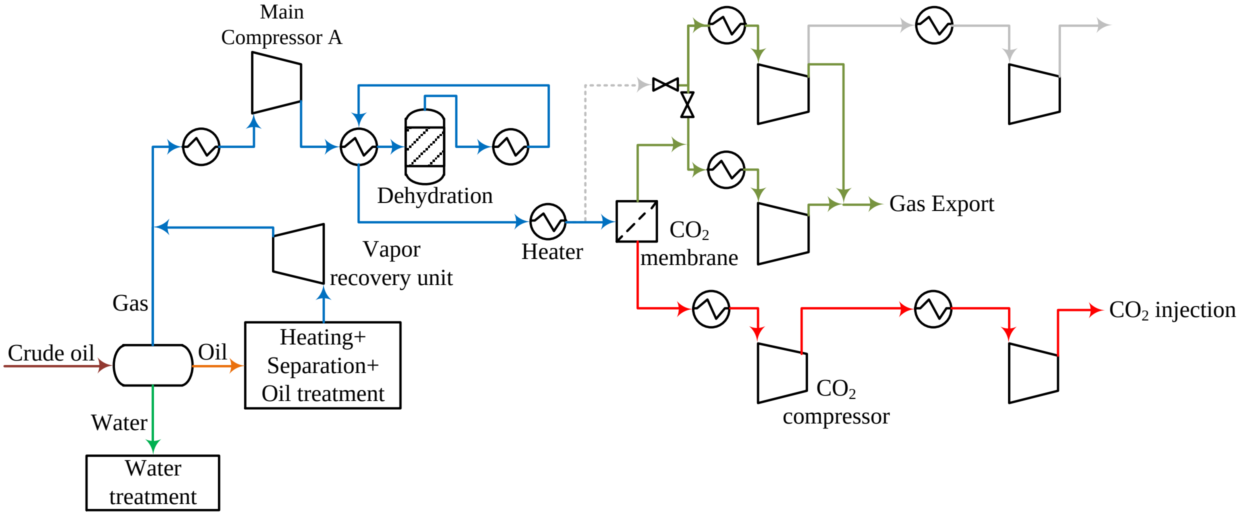

Fig. 5. Simplified scheme of the operational mode 3.

4. Results and discussion

Table 2 presents the results obtained from mass balance of three operational modes. Mass flow rates refer to the mass balance of the separation process, see Fig. 2, in which inlet mass flow rate is the sum of crude and dilution water, and outlet mass flow rate is the sum of oil, water, gas (export, injection, fuel) and CO_2. Imported gas for fuel purpose is not part of the mass balance in the separation process. As can be seen from this table, the mass flow rate of oil increases from mode 1 to mode 3, which is accorded with the characteristics of the operational modes, consequently, the mass flow rate of water reduces for this mode variation. Additionally, Table 2 shows the distribution of the mass flow rate of separated gas.

Table 2. Mass flow rates of the operational modes [t/h]

Stream	*Mode 1* (maximum water/CO_2)	*Mode 2* (50% BSW)	*Mode 3* (maximum oil/gas)
Crude	1219.2	1219.2	1219.2
Oil	180.6	453.7	921.6
Water	891.9	659.5	60.3
Dilution water	9.8	24.4	48.8
Gas (export)	-	34.8	257.2
Gas (injection)	156.6	65.2	-
Gas (fuel)	-	4.6	11.1
CO_2 (injection)	-	25.8	17.8
Imported gas (fuel)	4.0	-	-

In the Table 3 are presented some exergy streams calculated for the FPSO. From this data we can see that the product exergy notably rises when the crude oil composition has more oil/gas quantity. Similar behavior is observed in the utilized exergy and in the gas turbine power. These results indicate that there is a significant positive correlation between exergy streams presented in Table 3 and the features of the operational modes, mainly, of the compositions of the crude oil. A higher oil/gas quantity in the crude oil composition implies more exergy requirements in the compression trains resulting in more exergy resources.

Table 3. Exergy streams of the operational modes

Stream	*Mode 1* (maximum water/CO_2)	*Mode 2* (50% BSW)	*Mode 3* (maximum oil/gas)
Product exergy [kW] $\sum \dot{B}_P - \dot{B}_M$	6828	15875	37401
Utilized exergy [kW] $\dot{B}_U$	52673	64720	156770
Gas turbine power [kW]	14810	18250	44220

Results of performance criteria of three operational modes are presented in Table 4. Operational mode 2 presents the highest exergy efficiency followed by the operational mode 3. The operational mode 1 has the lowest exergy efficiency. The positive correlation between operational mode and exergy efficiency for modes 1 and 2 is not totally clear due to the exergy efficiency reduction when operational mode changes from 2 to 3.

It is relevant to take into account that the mode operation depends on the crude oil composition but it implies variations in the compression schemes and pressure levels. In the mode 1, all separated gas is injected at 494 bar, while in the mode 3 all gas is treated in the CO_2 removal unit and then it is exported at 250 bar, and the separated CO_2 is injected at 494 bar. The mode 2 has gas exportation at 250 bar, gas injection at 494 bar and CO_2 injection at 494 bar. In mode 1, the pressure and mass flow rate for the gas injection process may have a significant effect on the power consumption and on the low value of exergy efficiency in comparison with modes 2 and 3. It is not simple to find a conclusive cause of the lowest efficiency in mode 1, but it appears that the mode 2 has the highest exergy efficiency because of the combination of all capabilities of the FPSO (gas exportation, gas injection and CO_2 injection). The assumed distribution of gas for treatment and export purposes and gas injection (50%/50%) may not be the best combination in order to obtain the highest exergy efficiency. Mode 3 shows that when all gas is treated and exported, the exergy efficiency is high but it is slightly lower than mode 2 operating with the conditions assumed in this work. A further study is needed to establish the influence of FPSO variables (pressures, mass flow rates, among others) on its performance.

Table 4. Exergy efficiency, specific exergy consumption and renewability exergy index of operational modes

Exergy criteria	*Mode 1* (maximum water/CO_2)	*Mode 2* (50% BSW)	*Mode 3* (maximum oil/gas)
Exergy efficiency	13.0 %	24.5 %	23.9 %
SEC_{volume} [MJ_b/Sm^3o.e]	898	434	411
Renewability exergy index	0.069	0.131	0.127
CO_2 emissions [kg/h]	10739	12928	31212
CO_2 emissions per unit of exergy contained into the products [kg_{CO2}/GJ_b]	1.65	0.69	0.65

The specific exergy consumption presents a significant negative correlation with the operational mode. Maximum oil/gas composition mode (mode 3) has the lowest SEC_{volume} whereas maximum water composition has the highest SEC_{volume}. This behavior of the specific exergy consumption indicator can be explained in part by the high influence that the processed oil has in the denominator of (7). It is interesting to note that SEC_{volume} in the modes 2 and 3 is lesser than 50% of SEC_{volume} in mode 1 which indicates that a crude oil composition with high water content is the worst scenario to process oil and gas in the FPSO. The findings of the current study are consistent with those of Voldsund et al. [11] for gas and oil offshore platforms. It can be seen that SEC_{volume} of FPSO are slightly higher than SEC_{volume} of the offshore platforms, excepting for the platform A.

A comparison between the renewability exergy indexes for the three operational modes suggests that the mode 1 is the less favorable for the operating of the FPSO. The modes 2 and 3 have a renewability exergy index about the double of the λ in the mode 1. It indicates that the modes 2 and 3 are more environmentally favorable than the mode 1. Renewability exergy index with a value less than 1 implies that the process is environmentally unfavorable. In the case of the FPSO analyzed, the low value of λ is due to the utilization of non-renewable resources. The use of gas fuel exergy to satisfy the requirements on the FPSO affects negatively the value of renewability exergy index. Further, can be observed than a significant increment of the exergy efficiency (modes 2 and 3 vs. mode 1) maintains the value of λ far below of 1 indicating that FPSO operations are far to be environmentally favorable. The orders of magnitude of renewability exergy indexes calculate in this work are comparable with those obtained for fixed offshore platforms in [12].

CO_2 emissions presented in Table 4 are those produced in the combustion process of the gas turbine. Table 4 shows that CO_2 emitted to the atmosphere increase when the operational mode changes from the first to the third mode. This increment of carbon dioxide is associated with the power requirement of the processing plant for each operational mode and it supposes that a crude oil with more quantity of oil/gas implies higher amount of power demanded by the operational modes of the FPSO. This indicator is useful in order to show the effect of the operational mode on the greenhouse effect.

In this work, CO_2 emissions per unit of exergy contained into the products have been used as an additional indicator to assess the environmental effect of the gaseous emissions from FPSO. It is calculated as the emitted mass of CO_2 normalized per unit of exergy of the product streams of the FPSO. Table 4 presents the obtained results for this indicator. It can be seen from this table that operational mode 1 has the highest value of CO_2 emissions per unit of exergy of products followed by the operational mode 2. Operational mode 3 has a value of normalized CO_2 emissions slightly lower than mode 2. These results establish that operational mode 3 has the highest environmental performance when CO_2 emissions are compared taking into account the normalization related to the exergy content of the products of the FPSO.

5. Conclusions

Three operational modes of a FPSO were assessed applying several exergy and environmental indicators. Variable crude oil composition and operating schemes for each mode do not permit to establish a defined tendency in the behavior of the exergy efficiency and the renewability exergy index, but it is clear that operational mode 1 has exergy and environmental disadvantages in comparison with modes 2 and 3.

Operational mode 1 has the lowest exergy performance according with performance indicators used in this study. It is important to evaluate other distributions of gas for treatment and export purposes and gas for injection in the mode 2 in order to obtain more details about the exergy performance of the FPSO when the crude oil composition is different of 50% BWS.

Operational mode 3 has lower specific exergy consumption in comparison with the other modes. It indicates that the mode 3 might be the best exergy scenario for the operation of the FPSO taking into account the analogy between the specific exergy consumption and the specific energy consumption, which is a energy indicator recognized by oil and gas industry. The advantage of the operational mode 3 is also evidenced by the CO_2 emissions per unit of exergy contained into the products.

This work establishes that FPSO exergy performance has a strong dependence of the operational modes. A further study with more focus on the influence of other possible conditions of the operational modes on the FPSO exergy performance is therefore suggested. A more detailed exergy assessment should be done in order to know the exergy performance in the sub-systems of the FPSO.

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Nomenclature

b	Specific exergy, J/kg
$\dot{B}$	Exergy rate / flow rate, kW
$\dot{B}^Q$	Thermal exergy, kW
cv	Control volume
h	Specific enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, t/h
Q	Heat
$\bar{R}$	Gas constant, J/(mol K)
s	Specific entropy, kJ/(kg K)

t Tonnes

T Temperature, (°C, K)

$\dot{V}$ Volumetric flow rate

$\mathrm{W_{net}}$ Net power

$\dot{W}$ Power, kW

x Mole fraction, -

Abbreviations

BSW Basic sediment and water

FPSO Floating, production, storage and offloading vessel

GOR Gas-to-oil ratio, standard cubic meters to stock tank cubic meters sm^3/stm^3

OGP International Association of Oil & Gas Producers

SEC Specific exergy consumption

VRU Vapor recovery unit

Greek symbols

γ Activity coefficient, -

η Efficiency, -

λ Renewability exergy index, -

Subscripts

0 Restricted dead state

b, B Exergy

ch Chemical

$\mathrm{CO2}$ $\mathrm{CO_2}$

$dest$ Destroyed

$deac$ Deactivation

$disp$ Disposal

$emis$ Emissions

fos Fossil

i i-th component in the mixture

in Inlet

k Kinetic

M Mixture

out Outlet

p Potential

P Product

$prod$ Product

ph Physical

U Used

Superscripts

i i-th component in the mixture

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