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Study of waste heat recovery potential and optimization of the power production by an organic Rankine cycle in an FPSO unit

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to explore the alternatives for waste heat recovery in a floating production storage and offloading (FPSO) platform to meet the demand for heat (from hot water) and to maximize the electric power generation through the organic Rankine cycle (ORC) with purpose to increase the overall thermal efficiency of the process and reduce CO_2 emissions. Two different cycles' configurations are explored (simple and regenerative) using exhaust gases from the gas turbines as the heat sources for the ORC and the cogeneration system. The curves of the GE LM2500 and GE LM2000 turbines are modeled together with the water heating systems and the organic Rankine cycle. The model is solved using a genetic algorithm optimization method, whose objective function is set to meet the electric power demand for the FPSO platform. The purchased equipment costs of the ORC, the reduction in fuel consumption and CO_2 avoided are estimated. Waste heat recovery meets the heat demand and contributes up to 21% of the electric energy demand, which increases the overall efficiency of the system, and improves the utilization factor by up to 10.8% and 19.2%, respectively. There is an average reduction of 22.5% in fuel consumption and CO_2 emissions during the lifetime of the FPSO. The economic analysis based on the NPV shows that a US$12.55 million return on investment is possible, in addition to reducing the initial investment cost by US$14.2 million through the exclusion of the GE LM2500 gas turbine at project implementation.

1. Introduction

One of the world's major concerns today is environmental pollution as well as its consequences. With the growth in industrialization, the problem has worsened, and environmental agencies have become more demanding in relation to CO_2 emission criteria. According to the International Energy Agency (IEA), greenhouse gas emissions and the concentration of these gases in the atmosphere has steadily increased. One of the main causes of this increase is the energy sector, which accounts for approximately two-thirds of all anthropogenic emissions that will cause irreversible impacts to the planet [1].

For the oil and gas industry, methane and carbon dioxide are the two most important greenhouse gases, the former having a greater capacity to capture solar radiation in the atmosphere, which makes it a potential cause of short-term warming. The large expansion in oil and gas exploration due to the discovery of the pre-salt layer in Brazil has seen the increase in the use of offshore platforms [2]. Although Brazil is not obliged to reduce its CO_2 emissions, a commitment to reduce them is assumed for the year 2020. In Brazil, the main sources of CO_2 emissions are changes in land and forest use due to over-burning and deforestation, contrary to other countries where burning fossil fuels is the main source of emissions. However, from the year 2020, it is forecasted that Brazil will reach a situation similar to those of industrialized countries, which requires the adoption of control policies on the burning of fossil fuels [3].

The recovery of residual heat from offshore processes with the organic Rankine cycle (ORC) has been explored by several researchers around the globe for the purpose of generating power without the need for additional burning of fossil fuels. Mondejar et al. [4] conducted a study of an ORC integrated into a passenger vessel of the M/S Birka Stockholm cruise ship. It was evaluated by an off-design model based on optimized design conditions. Using the ORC, 22% energy was obtained in relation to the total demand of energy on board. Suarez et al. [5] studied a practical application of exhaust gas waste heat recovery from the engines of the Aframax tanker. A conventional Rankine cycle was compared to the ORC using benzene, heptane, hexamethyldisiloxane, toluene, and the R245fa. The installation of a waste heat recuperator allows an annual fuel saving of €154 k and a reduction in CO_2 emissions of 705 t. The fuel consumption and CO_2 emissions fall by 17% using the ORC when compared to the conventional Rankine cycle. Song

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Nomenclature

Latin and greek symbols

D	demand (MW)
h	enthalpy (kJ/kg)
i	discount rate (%)
I_{fuel}	income saved fuel consumptions (US$/yr)
I_{CO_2}	income saved CO_2 emissions (US$/yr)
L	workload (%)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
mf	mass fraction (%)
M_f	maintenance factor
P	pressure (Bar)
$\dot{Q}$	heat energy (MW)
T	temperature (°C)
$\dot{W}$	power (MW)
ΔT	temperature difference (°C)
ε_u	utilization Factor (%)
$\bar{\eta}$	average efficiency (%)
η	efficiency (%)

Abbreviations

Ar	argon
API	American petroleum institute
C1, C2, C3	compressor 1, 2 and 3
CC1, CC2, CC3	combustion chamber 1, 2 and 3
CO_2	carbon dioxide
DC	direct costs
EES	engineering equation solver
FPSO	floating production storage and offloading
FCI	fixed-capital investment
GWP	global warming potential
GT	gas turbine
GA	genetic algorithm
GE	general electric
H_2O	water
IEA	international energy agency
IC	indirect costs
N_2	nitrogen
O_2	oxygen
ORC	organic Rankine cycle
ODP	ozone depletion potential
OF	objective function
PEC	purchased-equipment costs
R ORC	regenerative ORC
S ORC	simple ORC
TC	turbo-compressor
TCI	total capital investment

Subscripts and superscripts

1–24	refers to locations of GTs – ORC
A–H	refers to locations of ORC
atm	atmosphere
co	condenser
eco	economizer
eva	evaporator
sup	superheater
elect.	electric
fuel	fuel
gen	electric generator
in	input
mix	mixture
max	maximum
ml	logarithmic mean
n	mixture components
ORC	organic Rankine cycle
ove	overall
OTB	once-through boiler
p	pump
pp	pinch point
r	real
rc	heat recovery
re	regenerator
s	isentropic
sL	saturated liquid
sv	saturated vapour
t	turbine
up	upper
water	water

et al. [6] studied the waste heat recovery of a marine diesel engine. There was an efficiency increase of 10.2% for the marine diesel engine, and the system proved to be economically attractive. Larsen et al. [7] compared the conventional Rankine, the Kalina, and the ORC cycle for combined cycle application in conjunction with a large two-stroke marine diesel engine. The maximum power was obtained using the ORC cycle whereas the conventional Rankine cycle and the Kalina cycle produced ~75.0% of the ORC power. The thermal efficiency of the plant of the cycle combined with the ORC was 52.0%, whereas the Kalina and Rankine cycles resulted in 51.0% and 51.1%, respectively, making a possible increase in the overall efficiency of the plant of up to 2.6%. Pierobon et al. [8] conducted a study to determine which heat recovery technology is the most suitable for offshore installations. The results showed that the ORC presents better performance with respect to the Rankine steam, whereas the air-bottoming cycle modules are not interesting from the economic and environmental standpoints. Despite the high cost of the ORC equipment, the ORC turbogenerators are the solution to reduce CO_2 emissions in offshore installations. Girgin and Ezgi [9] conducted a thermodynamic study of an ORC to recover the waste exhaust gases from a diesel generator on a naval ship. In an ideal case, it was possible to produce 92 kW of power using toluene as the working fluid, in addition to saving 25,500 liters of diesel fuel and reducing 67.2 tons of CO_2 emission at the end of 1000 operating hours.

Several other studies related to ORC for waste heat recovery were performed. Soffiato et al. [10] evaluated the heat recovery from an ORC of three engines of a driven liquefied natural gas. Three ORCs were compared: simple, regenerative and two-stage ORCs. The results showed that the two-stage cycle reaches maximum net power corresponding to almost double the simple and regenerative ORC. Imran et al. [11] carried out a thermo-economical optimization study of a simple and regenerative ORC for waste heat recovery for a constant heat source. Thermal efficiency and specific investment cost was optimized to different working fluids. The results showed that the R245fa is the best working fluid and the simple ORC presents lower specific cost. Song and Gu [12] studied a dual-loop ORC for waste heat recovery of the engine exhaust gas and the jacket cooling water. Cyclohexane, benzene and toluene were evaluated in the high temperature loop whereas R123, R236fa, and R245fa were chosen for the low temperature loop. The results showed that the combination of cyclohexane and R245fa presents the maximum net power and the additional power generated correspond to 11.2% of the original power output of the engine. Cao et al. [13] proposed the ORC as a bottoming cycle for the heat recovery of exhaust gases from a gas turbine. Aromatic fluids were chosen as the working fluid in the ORC. The results showed that the thermal efficiency and the net power increase with the ORC's turbine inlet pressure. Moreover, toluene showed to be the more suitable working fluid for a gas turbine combined to the ORC.

Motivated by the growing emission of greenhouse gases, energy-efficient technologies have been increasingly exploited to make industrial processes more cost-effective and efficient, along with reducing emissions. In this context, the objective of this study is to explore the alternatives to meet the demand for heat from the hot water of the platform, and to use the residual heat to maximize the electricity generation by the ORC. Firstly, an analysis of FPSO platform is carried out as designed (base case), which is used for comparison with the proposed systems. In the sequence, the first proposal is to maintain the base case and insert the organic Rankine cycle for exhaust gases heat recovery of the main generation system composed of three gas turbines in most of the operating time. The second proposal is use only two gas turbines in the main generation system in all operation periods and to recover its waste heat from exhaust gas together with the exhaust gases from the turbine driving the CO_2 compression system. The developed model is solved using the genetic algorithm (GA) optimization method to maximize the power generated by the ORC and to determine the reduction in fuel consumption and CO_2 emissions. In addition, an economic feasibility study based on the net present value, accounting for the costs associated with the ORC equipment, the reduction in fuel consumption, and CO_2 emissions over the past 21 years of the FPSO operation is performed.

1.1. The organic Rankine cycle (ORC)

The ORC is similar to the conventional Rankine cycle, except that the working fluid is not water. In the ORC, an organic compound with a high specific mass is used. A disadvantage in using the Rankine cycle is the need to generate superheated steam to minimize moist steam, and to reduce the erosion in the blades of the turbine's last stages. In ORCs, superheating is not necessary for many substances, which, according to Ganapathy [14], results in a more efficient cycling.

According to Chen et al. [15], it is desirable to select working fluids that have high latent heat, high specific mass and low specific heat in the liquid phase, as they result in higher turbine power and smaller equipment size. Moreover, according to Reis [16], organic fluids must satisfy additional requirements besides those related to energy transfer capacity, such as parameters for the effect on the environment, namely ozone depletion potential (ODP), global warming potential (GWP), and their lifetime in the atmosphere.

Vélez et al. [17] had mentioned toluene as the fluid used by the company Triogen for heat recovery applications with heat source temperatures above 350 °C. In addition, Siddiqi et al. [18] investigated hydrocarbons from n-pentane to n-dodecane in comparison to water, benzene and toluene for applications in the ORC for the waste heat recovery of a gas turbine. They have found that if the heat source is at a higher temperature, i.e. 500 °C, n-dodecane and toluene are suitable fluids. In this article the exhaust gases from the gas turbine are above 480 °C; therefore, toluene will be the working fluid used in the analyses.

The simple and regenerative ORC configurations are shown in Fig. 1, where the letters represent the input and output properties of the ORC equipment. In the simple configuration, the working fluid is pressurized by the pump and absorbs heat from the hot source through the boiler. The fluid comes out of the boiler as saturated vapor or superheated fluid and enters the turbine for expansion. Thereafter, the fluid is cooled down by water to the saturated liquid temperature in a condenser. In the regenerative configuration, the fluid passes through the regenerator where it is preheated prior to its entry into the boiler.

1.2. Floating production storage and offloading (FPSO)

FPSO platforms are usually used in ultra-deep water areas far from the mainland, where is not economically viable to use units that are submersible or fixed to the seabed. According to Gallo et al. [2] technical specifications for an FPSO processing unit are designed according to the production field in which it will be installed. In this study, the oil reservoirs feature the production of natural gas with high levels of CO_2, which needs to be removed with processes included in the FPSO topside. Fig. 2 shows an example of an FPSO operating on the Brazilian Pre-salt in Santos Basin and Table 1 presents the general process specifications for the FPSO studied.

The simplified scheme of the processing plant and the main features of each subsystem are detailed in Gallo et al. [2].

2. Proposed systems

Electricity demand varies as the periods of oil and gas production change over time. Therefore, the generation system must be designed to meet all production stages. Fig. 3 shows the FPSO power demand to be supplied by the system's main turbines and the turbines driving the CO_2 compression train, along with the platform's operating timeline, for both processes existing in the current platform.

The gas turbines' energy generation at an FPSO platform must be exactly equal to the energy demanded by the platform; thus, to implement a system for generating power from residual heat, it is

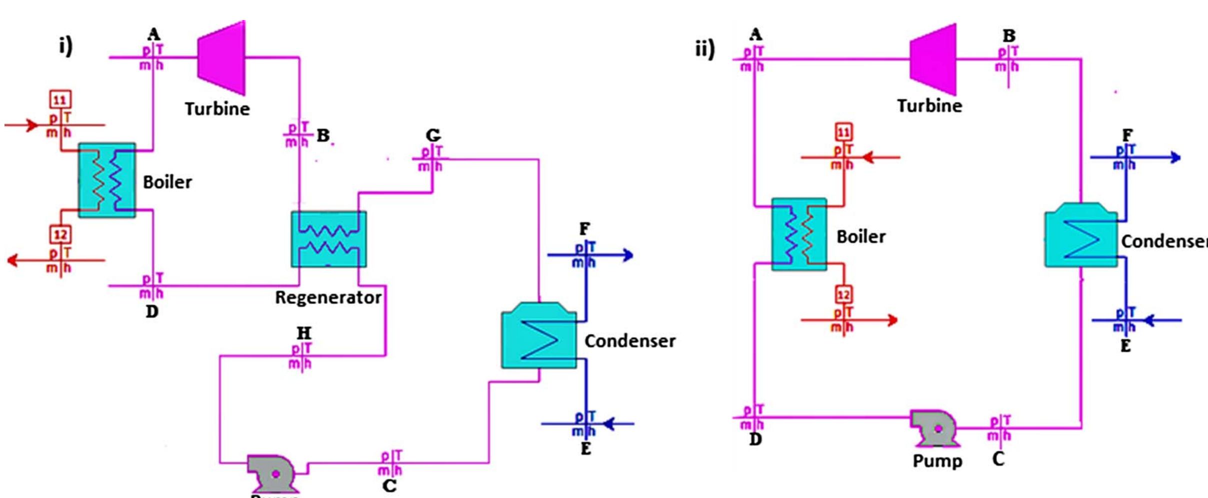

Fig. 1. (i) Regenerative ORC cycle (ii) simple ORC cycle.

Fig. 2. Pioneer Libra FPSO.
Source: [19]

Table 1
General process specifications for the FPSO.
Source: Gallo et al. [2]

Characteristic	Maximum capacity	Units
Oil and water processing	24.000	m^3/d
Oil storage	1600.000	bbl.
Oil processing	24.000	m^3/d
Produced water treatment	19.000	m^3/d
Treatment and gas handling	6000.000	Sm^3/d
Natural gas injection pressure	55.000	kPa
CO_2 injection pressure	45.000	kPa
Water injection	28.600	m^3/d

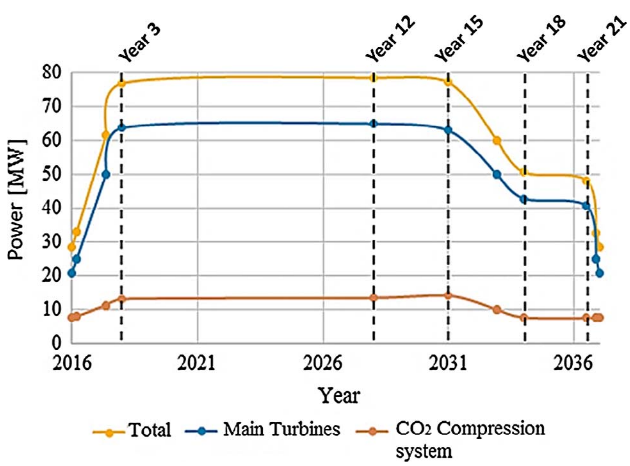

Fig. 3. FPSO power demand supplied by turbines.
Source: Gallo et al. [20]

important to verify the viability to meet the demand without excess or lack of power at each production level. Based on the limitations mentioned, the ORC is coupled to the exhaust gases of the gas turbines to recover the waste energy, contributing to power generation and reducing burning fuel in the gas turbines. In addition, an FPSO unit requires hot water in several production processes. The case study will also assess the heat supply for the production processes from the waste heat recovery of exhaust gases.

2.1. Base case – turbo-generators to meet the electricity and hot water demand

In the base case, the FPSO power demand is supplied by turbo-generators and its exhaust gases are used to meet the heat demand for treatment processes. In a real FPSO unit, there are three operating turbines for years 3, 12 and 15 and one in stand-by. For years 18 and 21 the number of operating turbines in parallel is reduced to two due to low energy demand, as shown in Fig. 3. This case will be useful for comparison with the proposed systems.

2.2. Case 1 – utilization of exhaust gases from the main gas turbines

For this case, the proposal is to maintain the real FPSO system and to insert an ORC for waste heat recovery. The modeling is conducted with the purpose of recovering the exhaust gases to meet the heat demand using hot water and power generation by ORC. The coupling of Figs. 4 and 1 results in the overall system for the study, where the numbers represent the properties at each node of the system.

The gas turbines of the main generation system used on the platform are the aeroderivative GE LM2500s and their performance is provided by the Thermoflex® software library. The nominal operating data of this turbine is presented in Table 2. By varying the turbine workload (between 50% and 100%) in the Thermoflex® software, it was possible to determine its behavior outside the nominal conditions (temperature of 15 °C and pressure of 1 atm). The results are used to generate polynomials as a function of the turbine workload, which are coupled to the modeling of the ORC and the water heating system in the Engineering Equation Solver (EES®) software.

Two perspectives are studied in the first case:

- Case (1A) Coupling the turbogenerators (GTs) and regenerative ORC using toluene as the working fluid (GTs + ORC [Toluene – Reg.]).
- Case (1B) Coupling the turbogenerators (GTs) and simple ORC using toluene as the working fluid (GTs + ORC [Toluene]).

2.3. Case 2 – utilization of exhaust gases from the main gas turbines and from the turbine driving the CO_2 compression train

In this case, the proposal is to use only two main gas turbines for electricity generation in all phases of the FPSO production and to take advantage of the exhaust gases from the main turbines as the heat source by the ORC, together with the exhaust gases from the turbine driving the CO_2 compression system as the heat source by the water heating system. The CO_2 compression unit is an already existing process on the platform studied and is a technology developed to increase the level of oil extracted from the already existing wells through the injection of CO_2 (see [2]). The coupling of Figs. 5 and 1 results in the overall system for the study.

The model used for the main turbines is the same as in the previous case. The turbine used for the CO_2 compression system is the GE LM2000, as shown in Table 2.

Two perspectives are studied in the second case:

- Case (2A) Coupling the GTs, GT_{CO2} and regenerative ORC using toluene as the working fluid (GTs + GT_{CO2} + ORC [Toluene – Reg.]).
- Case (2B) Coupling the GTs, GT_{CO2} and simple ORC using toluene as the working fluid (GTs + GT_{CO2} + ORC [Toluene]).

3. Thermodynamic modeling of the coupled systems

3.1. Modeling the optimization problem for the genetic algorithm method

The proposed model presents variables with high interdependency. Therefore, the model is performed in such a way that the heat and electric energy demands are met simultaneously by waste heat recovery. Eqs. (1)–(3) show the dependence of the output parameters given the turbine operating loads (L_1,L_2,L_3), and T_{amb} and P_{amb} are the temperature and the pressure of the place where the turbines are installed, assuming that the ambient temperature and the gas turbine exhaust pressure is 25 °C and 1 atm, respectively.

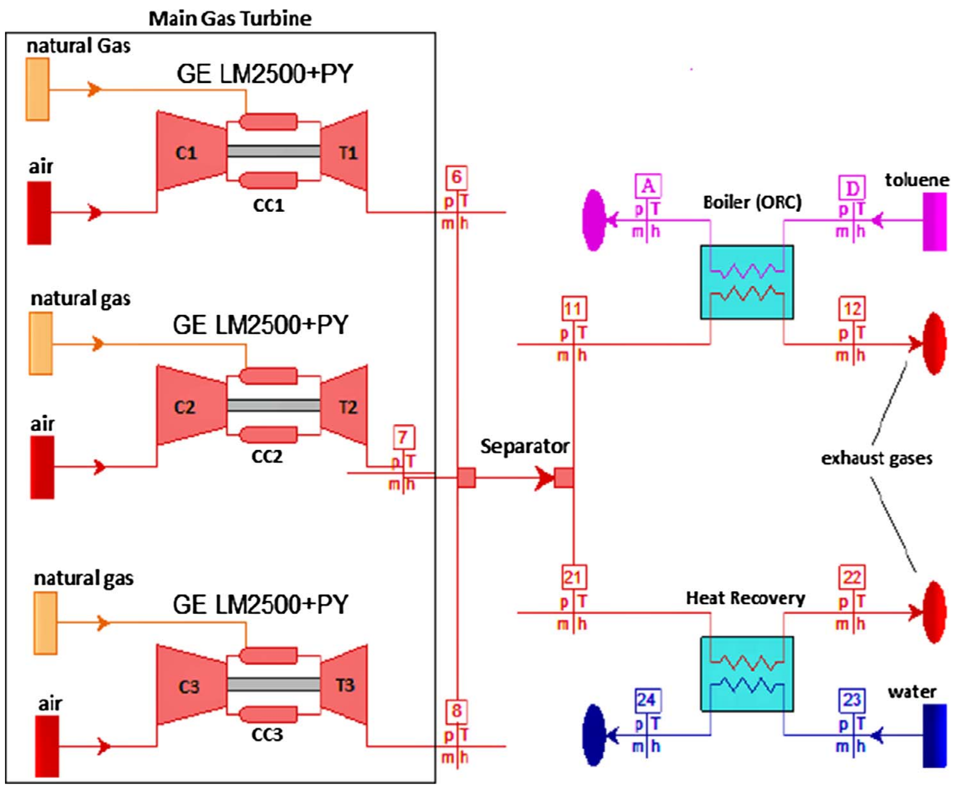

Fig. 4. Schematic of the ORC coupled to the main GTs – Case 1.

Table 2
Gas turbine specifications.
Source: Thermoflex® Software

Nominal ISO specifications	GE LM2500 + PY	GE LM2000
Nominal power [kW]	30,340	17,558
Nominal efficiency [%]	39.9	35.5
Pressure ratio [ad]	21.5	15.6
Exhaust temperature [°C]	510	474
Nominal air flow [kg/s]	83	62
Rotation [rpm]	6100	2300
Price [MMUS$]	14.2	–

$$T_6;P_6;\dot{m}_6;\dot{W}_{GT1};\eta_{GT1} = f(L_1;T_{atm};P_{atm}) \quad (1)$$

$$T_7;P_7;\dot{m}_7;\dot{W}_{GT2};\eta_{GT2} = f(L_2;T_{atm};P_{atm}) \quad (2)$$

$$T_8;P_8;\dot{m}_8;\dot{W}_{GT3};\eta_{GT3} = f(L_3;T_{atm};P_{atm}) \quad (3)$$

To determine the properties of the gas mixture exiting the GTs, it is assumed that the exhaust gases are mixed and that their compositions are unchanged, i.e., the number of moles of each component and, therefore, the total number of moles of the mixture remains the same. Table 3 shows the mean molar fraction of the exhaust gases of the gas turbine considered in the simulations.

For ideal gases, the enthalpy of the mixture is obtained from the weighed sum of each component of the mixture, as presented in Eq. (4).

$$h_{mix} = \sum_{n=1}^{5} mf_n \cdot h_n \quad (4)$$

After exiting the gas turbines, the gases are mixed and a portion is directed to meet the heat demand. The remaining gases are used for heat recovery in the ORC. Some considerations are made for the thermodynamic modeling of the ORC:

- Kinetic and potential energy changes are negligible;
- Steady operating conditions;
- Turbine isentropic efficiency is assumed to be 85% [21];
- Pump isentropic efficiency is assumed to be 85%;
- Fluid in the pump input is a saturated liquid;
- Electrical efficiency is considered to be 98%;
- Water is the cooling fluid in the condenser and the condensation temperature of the toluene is 40 °C;
- Pressure drop is disregarded in the heat exchangers.

According to [22], an organic fluid has a higher molecular weight, which increases the mass flow rate and gives better isentropic efficiency and less loss in the ORC turbine. Principles of mass and energy conservation are applied to each component of Fig. 1 and the results are presented in Tables 4 and 5.

The application of pinch point analysis in the heat transfer equipment is crucial in performing the optimization procedures. Fig. 6 shows the temperature profile of the heat exchange equipment in a regenerative ORC and Eqs. (5)–(9) show the relationship between temperature and pinch point.

$$T_{pp,1} = T_{sL} + \Delta T_{pp,1} \quad (5)$$

$$T_A = T_{11} - \Delta T_{pp,2} \quad (6)$$

$$T_D = T_B - \Delta T_{pp,3} \quad (7)$$

$$T_G = T_H + \Delta T_{pp,4} \quad (8)$$

$$T_{pp,3} = T_{sv} - \Delta T_{pp,5} \quad (9)$$

Heat demand, D_{water}, in the platform is represented by the energy balance in the heat exchanger of Figs. 4 and 5. Eq. (10) shows the results and is solved simultaneously with the demand for electric energy.

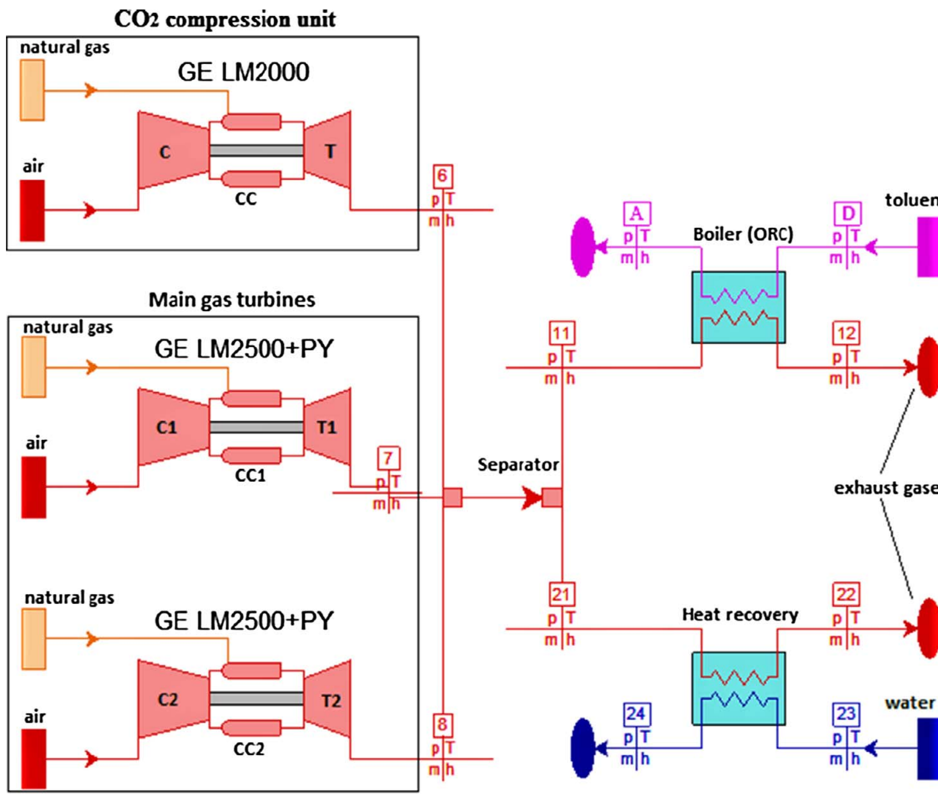

Fig. 5. Schematic of the ORC coupled to the GTs – Case 2.

Table 3
Composition of the GTs exhaust gases.

Component	Molar fraction [%]
N_2	75.22
O_2	14.34
H_2O	6.37
CO_2	3.16
Ar	0.91

Table 4
Energy balance in simple ORC components.

Turbine	$\dot{W}_t = \dot{m}_A(h_A - h_B)$ $\eta_t = \frac{h_A - h_{B,r}}{h_A - h_{B,s}}$	Energy balance Isentropic efficiency
Pump	$\dot{W}_p = \dot{m}_A(h_D - h_C)$ $\eta_p = \frac{h_{C,s} - h_D}{h_{C,r} - h_D}$	Energy balance Isentropic efficiency
Condenser	$\dot{Q}_{co} = \dot{m}_A(h_B - h_C) = \dot{m}_E(h_E - h_F)$	Energy balance
Heat Recovery	$\dot{Q}_{rc} = \dot{m}_A(h_D - h_A) = \dot{m}_{11}(h_{11} - h_{12})$	Energy balance

Table 5
Energy balance in the regenerative ORC components.

Turbine	$\dot{W}_t = \dot{m}_A(h_A - h_B)$ $\eta_t = \frac{h_A - h_{B,r}}{h_B - h_{B,s}}$	Energy balance Isentropic efficiency
Pump	$-\dot{W}_p = \dot{m}_A(h_H - h_C)$ $\eta_p = \frac{h_{C,s} - h_H}{h_{C,r} - h_H}$	Energy balance Isentropic efficiency
Condenser	$\dot{Q}_{co} = \dot{m}_A(h_G - h_C) = \dot{m}_E(h_E - h_F)$	Energy balance
Heat recovery	$\dot{Q}_{rc} = \dot{m}_A(h_D - h_A) = \dot{m}_{11}(h_{11} - h_{12})$	Energy balance
Regenerator	$\dot{Q}_{re} = \dot{m}_A(h_B - h_G) = \dot{m}_A(h_H - h_D)$	Energy balance

$$0 = m_{21}(h_{21} - h_{22}) + m_{23}(h_{23} - h_{24})$$
$$D_{water} = m_{23}(h_{23} - h_{24}) \tag{10}$$

The thermal efficiency of the ORC is defined as the ratio of the net power, $\dot{W}_{ORC}$, to the heat input the cycle, $\dot{Q}_{in,ORC}$, as shown in Eq. (11). The overall efficiency of the system is presented in Eq. (12) and is established from the ratio of the total power produced by the system (main gas turbines + ORC) to the energy released by the fuel in the combustion chamber of the gas turbines. The utilization factor defined by Eq. (13) refers to the portion of the energy supplied by the fuel to the system that is used for power generation or heat.

$$\eta_{ORC} = \frac{\dot{W}_{ORC}}{\dot{Q}_{in,ORC}} \tag{11}$$

$$\eta_{ove} = \frac{\sum \dot{W}_{GT} + \dot{W}_{ORC}}{(\dot{m}\cdot LHV)_{fuel}} \tag{12}$$

$$\epsilon_u = \frac{\sum \dot{W} + \dot{Q}}{(\dot{m}\cdot LHV)_{fuel}} \tag{13}$$

The constraints imposed on the system are as shown in Eqs. (14) to permit sufficient degree of freedom for the objectives to be achieved, where L_1, L_2 and L_3 are the workloads of turbines 1, 2 and 3; $T_{Máx.ORC}$ is the maximum temperature reached by the working fluid of the ORC, in which has the degree of freedom of the saturation temperature, T_{sat}, is defined by the upper pressure of the cycle, assumed as 25 bar. The upper limit of the maximum temperature, T_{up}, is defined such that it is below the auto-ignition temperature of the refrigerant, which for toluene is 480 °C [23]. The lower limit of the T_{12} above 110 °C was considered due to the restriction of the acid dew point and the narrow range for the exhaust gases' exit temperatures, T_{12} and T_{22}, after the heat recovery with the aim of increasing residual heat recovery by the ORC and the water heating system. That the pinch points should be greater than 10 °C is considered a constraint.

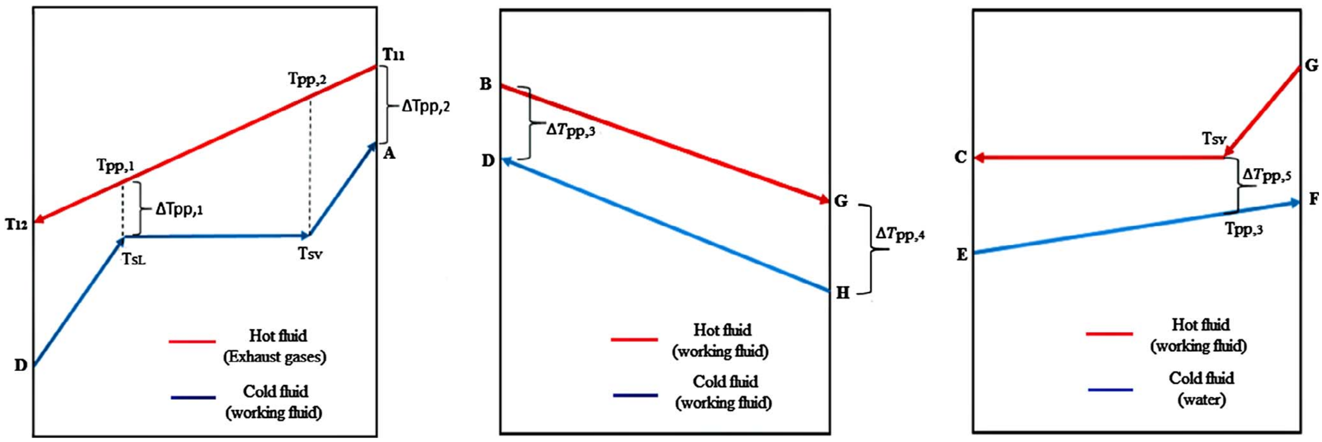

Fig. 6. Temperature profile in a boiler, a regenerator and a condenser.

Table 6
Genetic algorithm parameters.

Parameter	Setting
Generations	128
Individuals	32
Mutation Rate	0.7
Cross-over rate	0.85

Table 7
Power demand of the CO_2 compression turbine (TC).
Source: Thermoflex® Software

Period	TC [MW]
Year 3	12.74
Year 12	16.15
Year 15	16.07
Year 18	6.90
Year 21	6.86

Table 8
Breakdown of total capital investment (TCI).
Source: Pierobon et al. [8]

Total capital investment (TCI)	I + II
I. *Fixed-capital investment (FCI)*	DC + IC
A. Direct costs (DC)	
✓ Purchased – equipment costs (PEC)	
✓ Purchased – equipment installation	15% PEC
✓ Piping	35% PEC
✓ Instrumentation and controls	12% PEC
✓ Electrical equipment and materials	13% PEC
B. Indirect costs (IC)	
✓ (a) Engineering and supervision	4% DC
✓ (b) Construction costs and contractor's profit	15% DC
✓ Contingencies	10% of (a) and (b)
II. *Other outlays*	
✓ Startup costs	4% FCI
✓ Working capital	15% TCI
✓ Costs of licensing, research and development	7.5% FCI
✓ Allowance for funds used during construction	7.5% FCI

$$\begin{aligned} &50 \leqslant L_1[\%] \leqslant 100\\ &50 \leqslant L_2[\%] \leqslant 100\\ &50 \leqslant L_3[\%] \leqslant 100\\ &T_{sat} \leqslant T_{max.ORC}[^\circ C] \leqslant T_{up}\\ &110 < T_{12}[^\circ C] \leqslant 150\\ &110 < T_{22}[^\circ C] \leqslant 150\\ &\Delta T_{pp}[^\circ C] > 10 \end{aligned} \tag{14}$$

The model is solved by the genetic algorithm (GA) optimization method in the EES® software with the objective of meeting the heat demand and simultaneously optimizing the power generation supplied by the ORC to the FPSO platform, alleviating the operation of the main turbines to meet the total demand. This method is a heuristic technique to solve optimization problems and is inspired by evolutionary biology, as in the process of natural evolution, heredity, mutation and recombination. The GA uses the population of individuals, and each individual represents a solution to the problem. In analogy to biology, where the gene is the indivisible component of representation and all of the genes make up a chromosome together, information is encoded in chromosomes, and reproduction and mutation will cause the population to evolve. According to Deb [24], in relation to the gradient-based methods, the GA has a lower risk of convergence to local minimums as it seeks convergence to the global optimum. However, the computational effort is higher due to the large number of evaluations needed for the objective function. According to the EES® manual, the three parameters most responsible for identifying an optimum and the associated computing effort are the individuals in a population, the generations, and the maximum mutation rate. The GA parameters used in optimizations are specified in Table 6.

The objective function (OF) is modeled to obtain the required power demand in each phase of the FPSO platform operation, as presented in Eq. (15). The second term of the OF can assume values higher or lesser than 1; therefore, the minimization of the objective function is performed with absolute values.

$$OF = Min\left|1-\frac{D_{elect.}}{\dot{W}_{GT1}+\dot{W}_{GT2}+\dot{W}_{GT3}+\dot{W}_{ORC}}\right| \tag{15}$$

In case 1, in the production periods when there are only two main turbines in operation due to low energy demand, the modeling occurred in the same way as for the periods with three main turbines. However, one of the currents will no longer exist in the mass balance and energy in the mixer modeling, and L_3 and $\dot{W}_{GT3}$ are dropped from the constraints and objective function.

Table 9
Cost correlations for the different components.

Component	Cost correlation	Ref.
Pump	$PEC_p = 378\left[1+\left(\frac{1-0.808}{1-\eta_p}\right)^3\right]\dot{W}_p^{0.71}$	[8,27]
Generator	$PEC_{gen} = 60\dot{W}_{gen}^{0.95}$	[8,28]
Turbine	$PEC_t = -16610 + 716\ \dot{W}_t^{0.8}$	[29]
Once-through boiler	$PEC_{OTB} = 3650\left[\left(\frac{\dot{Q}eco}{\Delta T_{ml,eco}}\right)^{0.8}+\left(\frac{\dot{Q}eva}{\Delta T_{ml,eva}}\right)^{0.8}+\left(\frac{\dot{Q}sup}{\Delta T_{ml,sup}}\right)^{0.8}\right] + 11820\dot{m}_A + 658\dot{m}_{11}^{1.2}$	[8,30]
Regenerator (Finned-plate)	$PEC_{re} = 187 + 25A_{re}$	[8,31]
Condenser (Shell-and-tube)	$PEC_{co} = 30800 + 890A_{co}^{0.81}$	[8]

Table 10
Demand for hot water, electricity and CO_2 emissions for each production period.

	Year 3	Year 12	Year 15	Year 18	Year 21
D_{water} [MW]	44.21	42.96	40.84	45.99	39.66
$D_{elect.}$ [MW]	63.74	65.00	62.97	42.89	40.70
$\dot{m}_{fuel}$ [kg/s]	3.91	3.96	3.87	2.62	2.55
$\bar{\eta}_{GT} = \eta_{ove}$ [%]	35.90	36.19	35.83	36.05	35.2
ϵ_u [%]	60.85	60.11	59.05	74.68	69.51
CO_2 emissions (GT)					
$\frac{\dot{m}_{CO_2}}{D_{elect.}}\left[\frac{kg}{MW\cdot h}\right]$	602.46	599.87	605.78	600.41	612.23

In case 2, through the polynomial generated as a function of the gas turbine (GE LM2000) workload with the data provided by the Thermoflex® software, it is possible to obtain the mass flow and the temperature of the exhaust gases from the CO_2 compression system to meet the power demand for each FPSO operating period, as presented in Table 7.

Table 11
Optimization results of the coupling of the systems using the regenerative ORC– Case 1A.

	Year 3	Year 12	Year 15	Year 18	Year 21
L_1 [%]	61.16	52.34	70.04	60.02	82.85
L_2 [%]	54.63	50.16	50.24	91.57	53.84
L_3 [%]	82.5	98.63	75.27	–	–
$\dot{W}_{GT1}$ [MW]	16.29	13.94	18.67	15.99	22.09
$\dot{W}_{GT2}$ [MW]	14.55	13.35	13.37	24.43	14.34
$\dot{W}_{GT3}$ [MW]	22.00	26.32	20.06	–	–
$\dot{m}_{fuel}$ [kg/s]	3.44	3.48	3.40	2.52	2.34
$\dot{W}_{ORC}$ [MW]	10.90	11.37	10.86	2.45	4.25
η_{ORC} [%]	30.41	29.61	27.56	29.92	28.51
$\bar{\eta}_{GT}$ [%]	33.89	33.93	33.76	35.38	34.27
η_{ove} [%]	40.88	41.13	40.8	37.53	38.28
ϵ_u [%]	69.19	68.32	67.27	77.76	75.52
CO_2 emissions (GT + regenerative ORC)					
$\frac{\dot{m}_{CO_2}}{D_{elect.}}\left[\frac{kg}{MW\cdot h}\right]$	533.26	528.50	534.42	578.15	568.67

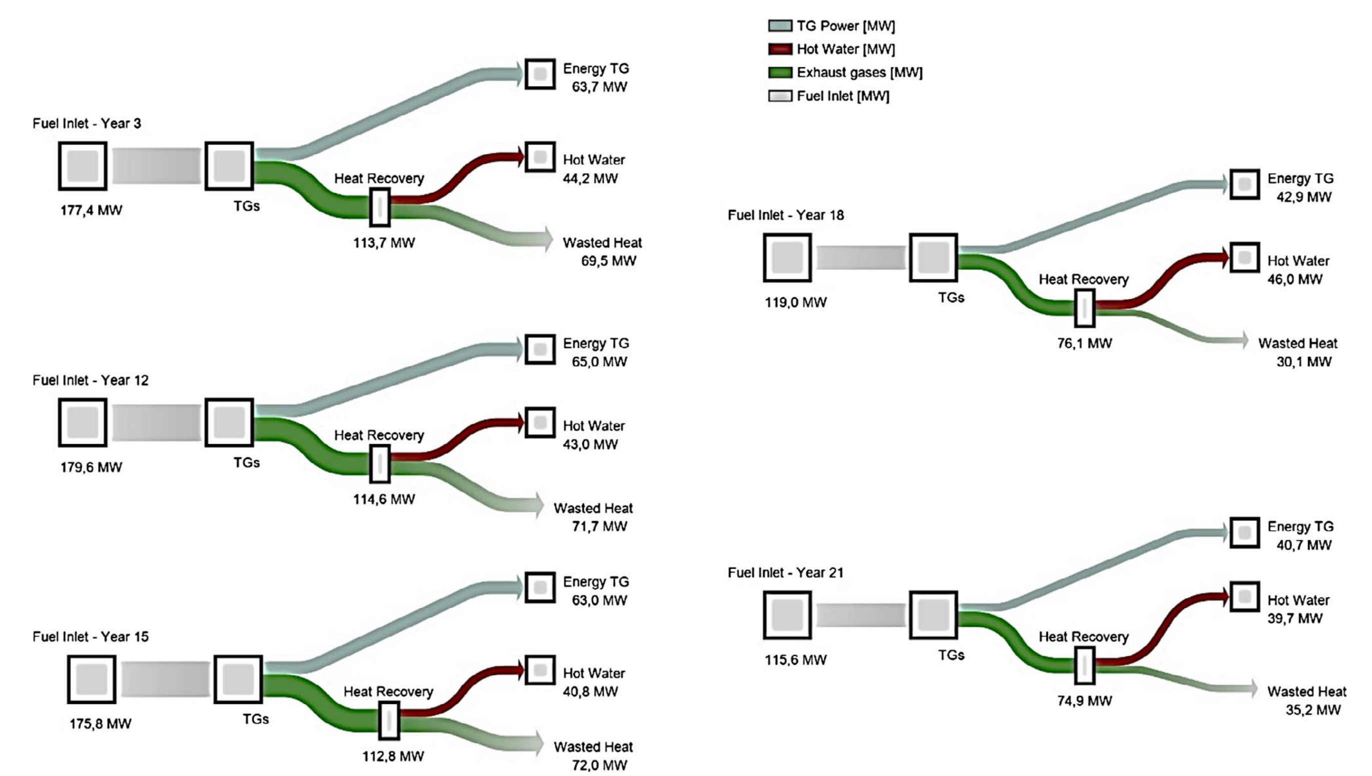

Fig. 7. Sankey diagram of the process – Base case – FPSO as designed.

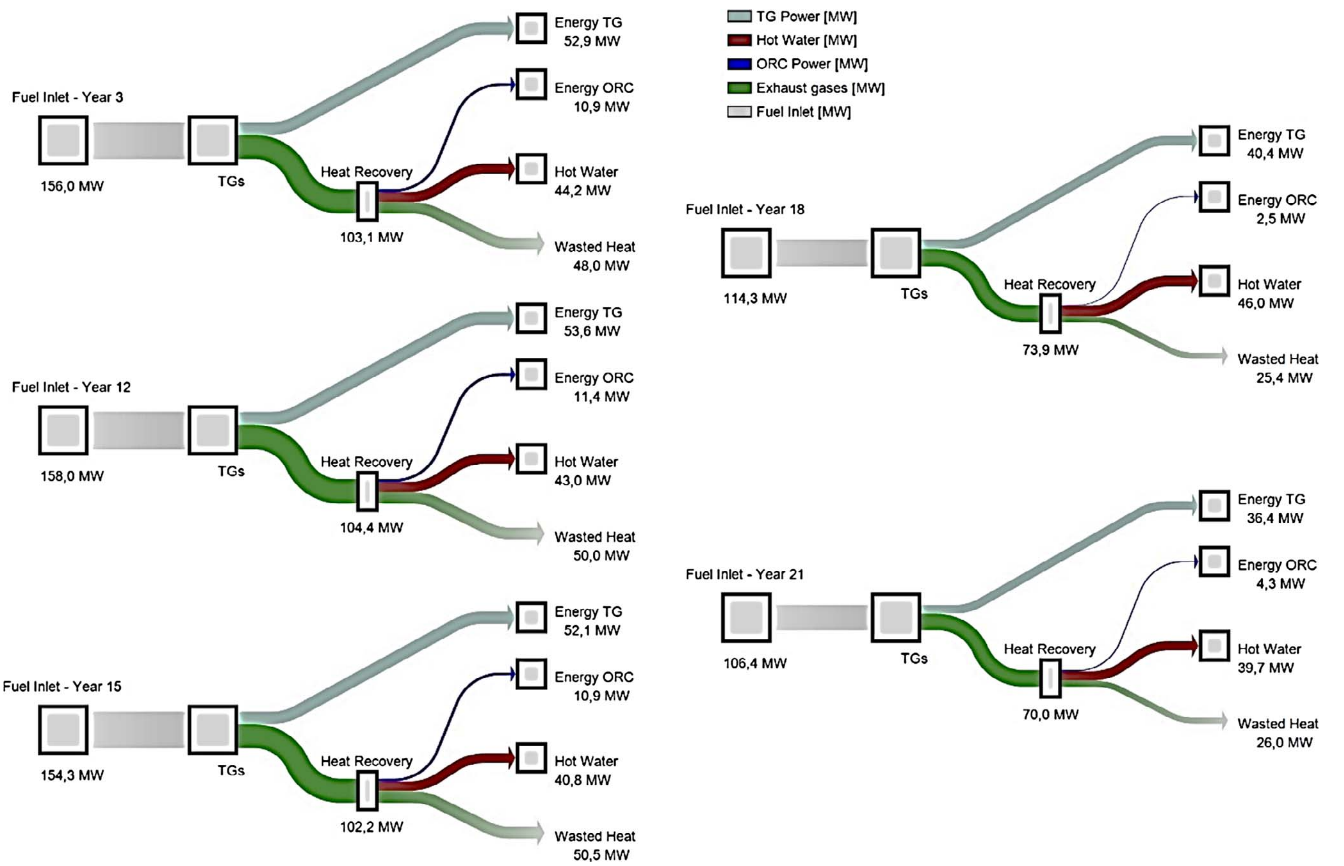

Fig. 8. Sankey diagram of the process (regenerative ORC) – Case 1A.

Table 12
Results of the coupling optimization of the systems using the simple ORC – Case 1B.

	Year 3	Year 12	Year 15	Year 18	Year 21
L_1 [%]	87.67	69.97	63.01	66.39	50.18
L_2 [%]	58.88	54.01	62.98	83.7	86.5
L_3 [%]	56.62	82.2	71.99	–	–
$\dot{W}_{GT1}$ [MW]	23.39	18.65	16.79	17.69	13.36
$\dot{W}_{GT2}$ [MW]	15.69	14.38	16.78	22.32	23.07
$\dot{W}_{GT3}$ [MW]	15.08	21.92	19.19	–	–
$\dot{m}_{fuel}$ [kg/s]	3.49	3.52	3.43	2.49	2.34
$\dot{W}_{ORC}$ [MW]	9.57	10.04	10.20	2.87	4.26
η_{ORC} [%]	24.67	24.72	24.87	24.47	24.38
$\bar{\eta}_{GT}$ [%]	34.14	34.36	33.9	35.36	34.25
η_{ove} [%]	40.18	40.64	40.46	37.89	38.25
ϵ_u [%]	68.12	67.48	66.7	78.5	75.53
CO_2 emissions (GT + simple ORC)					
$\frac{\dot{m}_{CO2}}{D_{elect.}}\left[\frac{kg}{MW\cdot h}\right]$	541.92	535.87	539.28	573.56	568.47

4. Economic analysis

The study of the economic viability of investment is an important step in the decision-making process. To estimate the total capital investment (TCI), the methodology proposed by Bejan and Moran [25], which has been applied by Pierobon et al. [8] for the study of heat recovery in an offshore platform is used. The inclusion of the ORC for heat recovery is the main proposal of this article; therefore, the estimation of the purchased-equipment costs (PEC) becomes necessary, besides the direct costs (DC) as well as the indirect costs (IC), as presented in Table 8.

The PEC of the ORC is calculated from the contribution of the pump cost (PEC_p), the electric generator (PEC_{gen}), the ORC turbine (PEC_t), the once-through boiler (PEC_{OTB}), the regenerator (PEC_{re}) and the condenser (PEC_{co}). The equipment cost correlations are presented in Table 9, where $\dot{W}_{gen}$ is the electric power produced by the generators, $\dot{Q}_{eco}$, $\dot{Q}_{eva}$, $\dot{Q}_{sup}$ and $\Delta T_{ml,eco}$, $\Delta T_{ml,eva}$, $\Delta T_{ml,sup}$ are the heat rates and the logarithmic mean temperature differences in an economizer, an evaporator, and a superheater, respectively. To estimate the heat transfer area of the regenerator, A_{Reg}, and of the condenser, A_{cond}, the overall heat transfer coefficients of 250 W/m²·k for a finned-plate and 500 W/m²·k for a shell-and-tube are used, as suggested by Coulson et al. [26]. The PECs are adjusted through the historical price index of 245.519 (2017).

The economic feasibility of the proposed system is calculated using the net present value (NPV) method presented in Eq. (16), where the maintenance and operation cost 10% of the total investment cost, i.e. $M_f = 1.1$ [28]; z and i are the lifetime of the investment and the discount rate, respectively; I_{fuel} is the fuel saving and I_{CO_2} is the yearly incomes associated with the avoided CO_2 emissions. Although Brazil is not required to reduce its CO_2 emissions, all countries that have adhered to the Kyoto protocol have a responsibility to contribute to the reduction. Countries that issue less than the allowed amounts can convert to the carbon credit, which can be negotiated with other countries that issue beyond what is allowed. This exchange model allows countries to meet their emissions targets through the purchase of carbon credits. The carbon credit price of 2.8 US$/ton ($CO_2$) [32] and the fuel price of 0.165 US$/m³ [33] are considered, whereby both are evaluated in the year 2016. Based on the information provided by the FPSO project, there are four turbo-generators (three turbo-generators in case 2) that take turns in the operating cycles to meet the demand throughout the year, which is compatible with three turbo-generators (two turbo-generators in case 2) operating 24 h/day for 365 days a year.

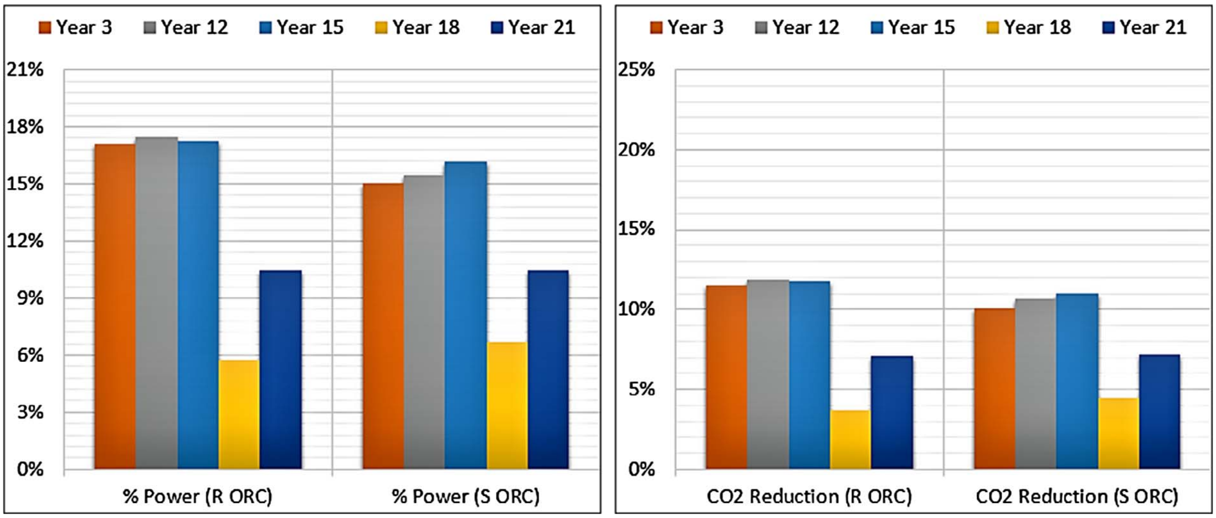

Fig. 9. Portion of power supplied by ORC and CO_2 Reduction – Case 1.

Table 13
Optimization results of the coupling of the systems using the regenerative ORC - Case 2A.

	Year 3	Year 12	Year 15	Year 18	Year 21
L_1 [%]	97.81	99.09	87.07	84.91	72.0
L_2 [%]	98.20	94.11	99.34	52.18	51.59
$\dot{W}_{GT1}$ [MW]	26.10	26.44	23.23	22.65	19.19
$\dot{W}_{GT2}$ [MW]	26.21	25.11	26.51	13.89	13.73
$\dot{m}_{fuel}$ [kg/s]	3.04	3.00	2.92	2.35	2.19
$\dot{W}_{ORC}$[MW]	11.44	13.44	13.22	6.33	7.76
η_{ORC} [%]	27.79	28.44	28.47	26.84	28.8
$\bar{\eta}_{GT}$ [%]	37.89	37.78	37.48	34.29	33.12
η_{ove} [%]	46.18	47.63	47.44	40.24	40.92
ϵ_u [%]	78.17	79.09	78.22	83.45	80.76
CO_2 emissions (GT + regenerative ORC)					
$\frac{\dot{m}_{CO_2}}{D_{elect.}}\left[\frac{kg}{MW\cdot h}\right]$	466.39	452.35	454.72	540.59	533.48

$$NPV = \sum_{z=1}^{21} (I_{fuel} + I_{CO_2})/(1 + i)^z - M_f\, TCI \tag{16}$$

5. Results

5.1. Base case – FPSO as designed

The general specifications provided by the FPSO platform design for hot water demand (D_{water}) and electric energy demand ($D_{elect.}$), based on Fig. 3, are listed in Table 10. Fuel mass flow ($\dot{m}_{fuel}$), gas turbine efficiency ($\bar{\eta}_{GT}$), utilization factor (ϵ_u) and CO_2 emissions are calculated from the modeling and optimization of only the gas turbines and the hot water system, to meet the FPSO's demands through the design and installation for each production period.

Fig. 7 shows the Sankey diagram illustrating the energy currents for each period. It is possible to note the portion of the energy released by the fuel in the gas turbine (fuel inlet), the portion that produces power (energy TG), the portion that produces heat (hot water) and the wasted heat portion (wasted heat). The results presented for this case will serve for further comparison with the cases studied.

5.2. Case 1

The proposal for this case is to maintain the system as in the base case (as designed) and insert the ORC (simple and regenerative) to the heat recovery of the exhaust gases from the main turbines. The analysis was based on the power and heat demand for each production period of the FPSO platform.

5.2.1. (1A) GTs + ORC [Toluene – Reg.]

In year 18 and year 21, there is a drop in the ORC generation output, because in these periods only two turbo-generators are in operation due to low power demand. The ORC contributes at least 5.7% of the total demand in year 18 and reaches close to 19% in year 12. Using the ORC for heat recovery, it is possible to achieve up to 41.13% in overall system efficiency, and in the worst case the efficiency reaches 37.53%, as shown in Table 11, which corresponds to an increase of 4.94% and 1.48%, respectively, over the base case. In all cases, there is a high utilization of the input energy of the system, which increases the utilization factor by up to 8.34% in year 3 and at least 3.08% in year 18, in relation to the base case.

The optimization results are used in the Thermoflex® software to calculate the CO_2 emissions. According to Blanco [34], CO_2 emissions calculated by the American Petroleum Institute (API) method and by the Thermoflex® software provide results with negligible error margins. It is possible to compare the reduction in the CO_2 emissions in relation to the base case shown in Table 10.

Fig. 8 shows the Sankey diagram for the results of the optimization process in each production period. The energy entering the GTs (fuel inlet) splits into two main portions. The useful part is converted into power by the gas turbines (energy TG) and the remainder is carried away with the exhaust gases. These gases are used for energy recovery in the heat recovery unit, in which a portion results in the electrical energy gain through the ORC (energy ORC) and the other is used for heat (hot water). Comparing Figs. 7 and 8, a significant reduction in fuel inlet and wasted heat in relation to the base case due to the insertion of the ORC is observed. In addition, the energy demand supplied by the gas turbines is reduced and complemented by the ORC.

5.2.2. (1B) GTs + ORC [Toluene]

Even the simple ORC system is a good option for electricity generation in the platform, increasing the overall thermal efficiency of the system up to 40.64%, reaching a 37.89% in the worst situation, as shown in Table 12, which corresponds to an increase of 4.45% and 1.84%, respectively, over the base case. In addition, there is also an expressive increase in the system utilization factor of 7.65% in year 15 and at least 3.82% in year 18 in relation to the base case.

There was no considerable difference between the regenerative cycle and the simple cycle with respect to the net power obtained. The

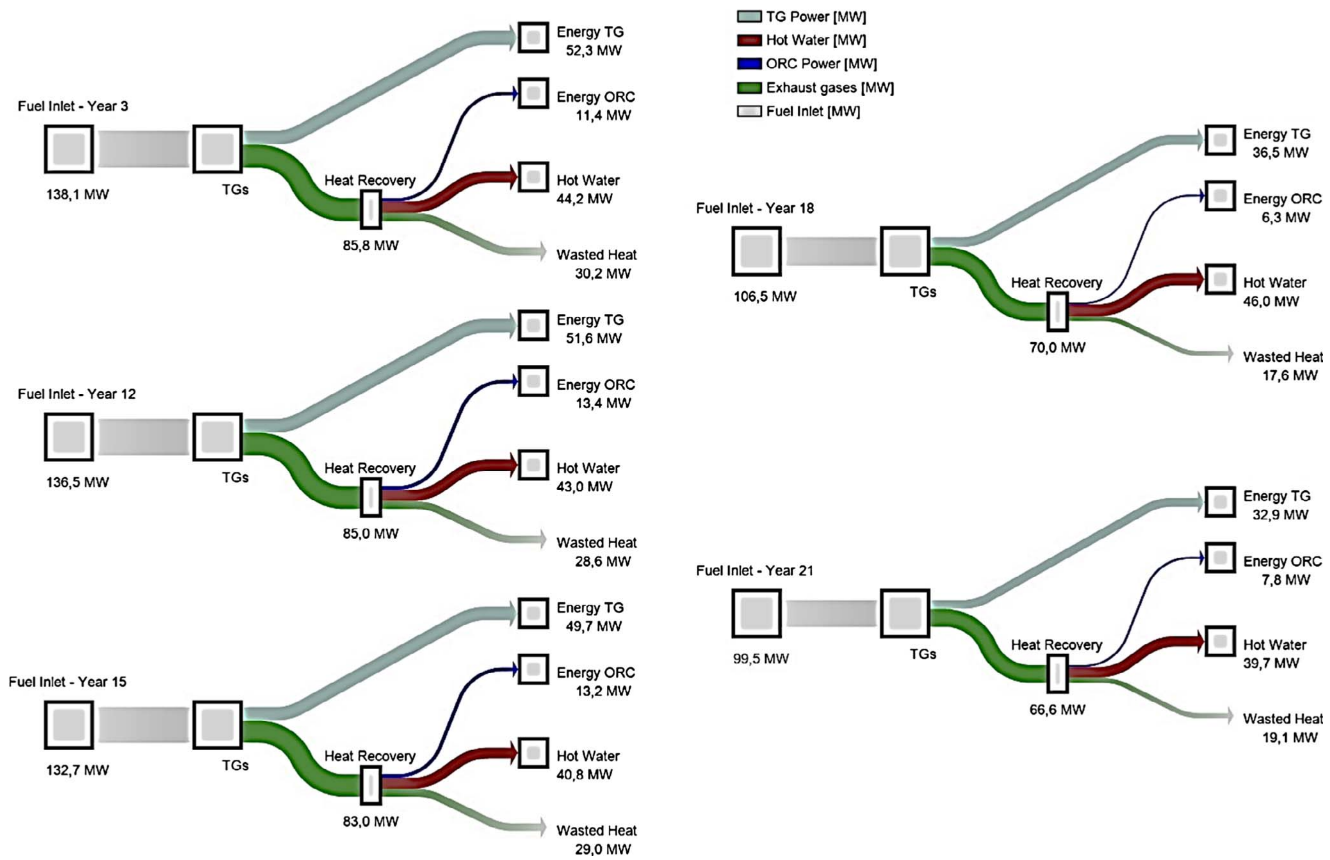

Fig. 10. Sankey diagram of the process (regenerative ORC) – Case 2A.

Table 14
Optimization results of the coupling of the systems using the simple ORC - Case 2B.

	Year 3	Year 12	Year 15	Year 18	Year 21
L_1 [%]	99.88	98.74	91.21	65.1	70.83
L_2 [%]	98.41	99.98	99.22	73.32	56.1
$\dot{W}_{GT1}$ [MW]	26.65	26.35	24.34	17.35	18.88
$\dot{W}_{GT2}$ [MW]	26.26	26.68	26.48	19.54	14.94
$\dot{m}_{fuel}$ [kg/s]	3.07	3.07	2.97	2.36	2.23
$\dot{W}_{ORC}$ [MW]	10.82	11.96	12.14	5.99	6.87
η_{ORC} [%]	24.53	24.66	24.93	24.78	24.35
$\bar{\eta}_{GT}$ [%]	37.98	38.0	37.66	34.47	33.43
η_{ove} [%]	45.75	46.57	46.66	40.07	40.22
ϵ_u [%]	77.48	77.33	76.94	83.0	79.44
CO_2 emissions (GT + simple ORC)					
$\frac{\dot{m}_{CO_2}}{D_{elect.}}\left[\frac{kg}{MW\cdot h}\right]$	470.52	462.16	461.91	543.78	542.57

thermal efficiency of the ORC is the main difference, which for the simple cycle is approximately 3% lower than the regenerative ORC, as can be observed by comparing the results presented in Tables 11 and 12.

Fig. 9 shows the portion of the energy supplied by the ORC with respect to the total demand for each period and the corresponding reduction in CO_2 emissions. The regenerative organic Rankine cycle (R ORC) serves up to 17% of the total energy generation demand. With the simple organic Rankine cycle (S ORC), a minimum of 6.6% of the electric energy is obtained through the recovery cycle in year 18, and reaching more than 16% in year 15. Heat recovery directly influences CO_2 emissions because less fuel is needed to meet the demand from the platform. In year 18, with the insertion of the regenerative ORC, at least a 3.7% reduction is obtained, reaching a maximum of 12% in year 12. The contribution of the simple ORC to the reduction in CO_2 emissions is at least 4.5% in year 18, reaching up to 11% in year 15.

5.3. Case 2

5.3.1. (2A) GTs + GT_{CO2} + ORC [Toluene – Reg.]

In this case, in addition to the main turbine exhaust gases, the exhaust gases from the gas turbine which drives the CO_2 compression system, are used. It is proposed that two main turbines meet the demand, which differs from the previous case where three turbines were used in some FPSO production periods. In this case, it is possible to meet the demand for electric power and heat from the platform in all oil production periods. In addition, the participation of the ORC in the total electric power increases by recovering heat from more exhaust gases.

Table 13 shows the results of the optimizations for the various periods studied for this case. Gas turbine efficiency in the first three periods is higher in relation to the base case. Main turbines are operating at an almost full load, as shown by L_1 and L_2, thus approaching the maximum efficiency point. In addition, the ORC supply a portion of the electricity demand, which contributes to a significant increase in the overall thermal efficiency of 11.61% in year 15 and at least 4.2% in year 18, and a representative increase in the utilization factor of up to 19.2% in year 15 and at least 8.8% in year 18.

The comparison between the Sankey diagrams presented in Figs. 7 and 10 show that, in this case, the system needs a fuel input much lower than the base case to obtain the same effects. This results in a much lower burning of fuel (natural gas), which consequently reduces CO_2 emissions and operating costs. In addition, turbo-generators are relieved (energy TG) and a large part of the energy demand is supplied by the ORC (energy ORC), resulting in a small current of wasted energy. The comparison between Figs. 8 and 10 shows the same trend as

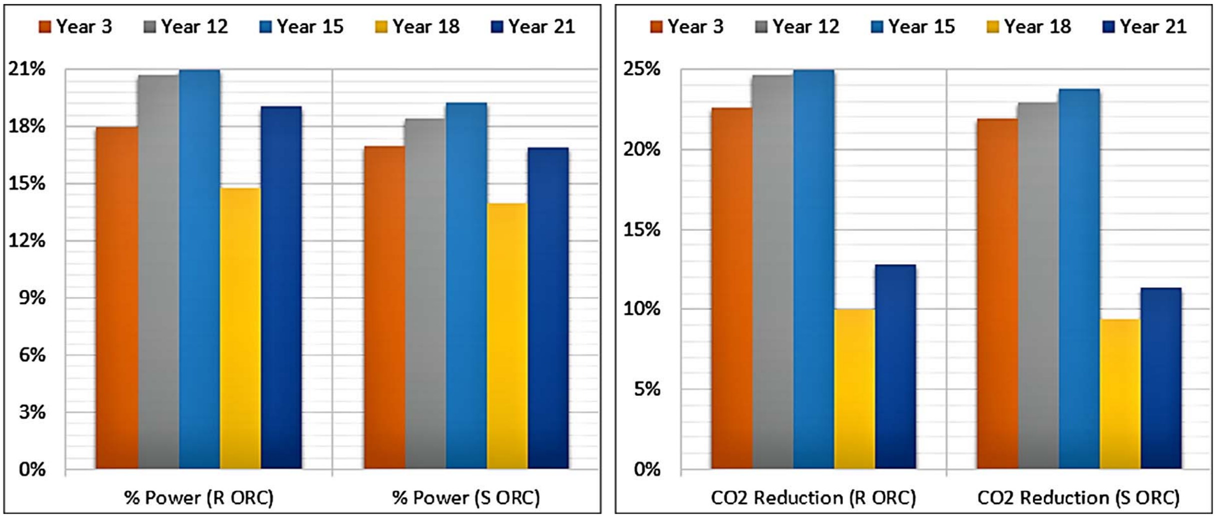

Fig. 11. Portion of power supplied by ORC and CO_2 reduction – Case 2.

observed in relation to case 1, which corroborates the superiority of case 2.

5.3.2. (2B) GTs + GT_{CO2} + ORC [Toluene]

The approach performed with the simple ORC meets the demands for all the operation periods of the platform and the results obtained are presented in Table 14. It is observed that the results overlap the base case, increasing the overall thermal efficiency of the system by 10.83% in year 15 and at least 4.02% in year 18. The increase in the utilization factor is more representative, reaching 17.89% in year 18 and at least 8.32% in year 18.

Although the simple cycle has shown to be slightly inferior to the regenerative cycle, it again confirms the advantages of reducing the number of gas turbines and the insertion of the ORC for heat recovery in the process due to high heat recovery and improved process efficiency. The maximum power generation in relation to the total demand by the simple ORC is 19.29% in year 15 and at least 13% in year 18. The largest CO_2 reduction also occurs in year 15, approaching 24%, and although the reduction in emissions is lower in year 18 (at least 9%), the proposed system continues to show interesting results.

Fig. 11 shows the percentage of electric energy supplied by the ORC in relation to the total demand for each period and the corresponding reduction in CO_2 emissions. The contribution of the regenerative ORC reaches 21% in year 15 and at least 14.78% in year 18 and a significant reduction of CO_2 is possible, reaching 25% in year 12 and at least 10% in year 18. The reduction in emissions is due to the fact that the GTs are operating close to their nominal load where the thermal efficiency is at its maximum, that is, the fuel energy is used better by the gas turbine, resulting in low fuel consumption. In all the analyzed periods, the ORC contribution to energy generation increases in relation to case 1.

Table 15
Fuel and CO_2 average.

System	$\dot{m}_{fuel}$(kg/s)	Fuel economy[a] (US\$/h)	$\dot{m}_{CO_2}$(kg/h)	CO_2 avoided[a] (US\$/h)	Reduction[a] (%)
Base case	3.38	–	33273.3	–	–
Case 1A	3.01	281.03	29684.9	10.04	10.9
Case 1B	3.03	263.50	29963.2	9.26	10.4
Case 2A	2.62	574.69	25708.8	21.18	22.5
Case 2B	2.68	532.24	26237.4	19.70	20.7

[a] In relation to the base case.

5.4. Preliminary economic analysis results

The estimation of the average reduction in fuel and CO_2 emission over 21 years of platform operation is performed by the weighted average of the fuel consumption, $\dot{m}_{fuel}$, and CO_2 emissions using a numerical integration through the approximation of Fig. 3 by known geometric figures. The results of average fuel consumption and CO_2 emissions, as well as the price of fuel saving and CO_2 avoided are shown in Table 15. In all cases, there was a considerable reduction in fuel consumption and CO_2 emissions in relation to the base case, which reduces the fuel cost and directly affects the cost of electricity production. The fuel economy is up to US$574.69/h using case 2A, associated with a return of US$21.18/h due to CO_2 avoided, corresponding to a significant reduction of 22.5% in relation to the base case.

Fig. 12 presents the sensitivity analysis of various discount rates, from 2% to 12% per year. It is observed the great influence of the discount rate in the net present value (NPV). In cases 1A and 1B, the implementation of the proposed system becomes economically unfeasible for the discount rates from 5.0% per year. The cases 2A and 2B are feasible for the discount rate of up to 10% per year; however, it is important to note that the composition of the economic analysis did not take into account the reduction in the initial investment cost of US$14.2 million, which is the avoided cost of one GE LM2500 + PY. If the initial investment is accounted for, the project becomes feasible even for the discount rate of 12% per year.

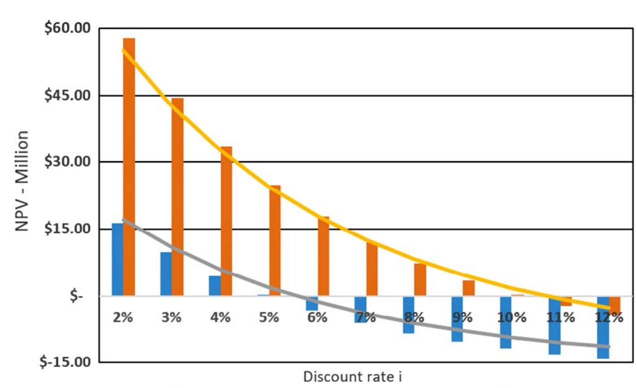

Fig. 12. NPV as a function of the discount rate i.

The Brazilian development bank [35] presents the current value of the long-term discount rate in Brazil of 7% per year. Therefore, for case 2A, NPV equals to US$12.02 million and for case 2B, NPV equals to US $12.55 million, presenting a slight advantage of 4.27% in the inclusion of the simple ORC for heat recovery. According to the presented methodology, the systems proposed in cases 1A and 1B are not economically feasible for the current economic situation of the country.

6. Conclusions

FPSO platforms have been increasingly used for oil exploration in ultra-deep and offshore waters. To address the need for improvements in the production process as well as the generation of electricity in its production phases, it is essential to invest in efficient technologies that will reduce costs and the emission of carbon dioxide in the atmosphere.

From these perspectives, the ORC has great potential for energy recovery with heat sources of different characteristics in the FPSO platform. This is an added advantage in the production process, as well as an improvement in the energy utilization of the burning of fossil fuels to meet the demand for electricity and hot water from the platform. The optimization method with GA proved to be effective in the resolution of the thermodynamic model.

The second case was the more advantageous and the more interesting between the two cases analyzed. It is proposed that in all production periods, power generation should only be carried out with two gas turbines and its exhaust gases and exhaust gases of CO_2 compression turbine should be profited as a heat source by the ORC. It is possible to meet the heat demand and contribute up to 21% in the electric energy demand and reduce CO_2 emissions by up to 25% using the regenerative ORC for heat recovery. The overall efficiency of the system is greatly influenced because the gas turbines work closer to the nominal point, which improves their thermal efficiency. Consequently, the overall efficiency in relation to the base case is increased by 10.83% in year 15 and at least 4.02% in year 18. Moreover, the utilization factor reaches a sharp increase of up to 19.2% in year 15 and at least 8.8% in year 18. The results did not show large differences between the simple and regenerative ORCs.

The study presented encouraging results in the implementation of the ORC for heat recovery, presenting an average of 22.5% reduction in fuel consumption and CO_2 emissions over the lifetime of the FPSO. The economic analysis allows us to be more judicious of the implementation viability and the modification of the current project. Maintaining the characteristics of the existing FPSO project, the insertion of the ORC is only feasible at a discount rate less than or equal to 5%. Nevertheless, the proposed modification to reduce to two operating turbines is feasible for a discount rate of up to 11%. The net present value of approximately US $12.55 million is obtained only by accounting for the reduction in fuel consumption and CO_2 emissions avoided during the FPSO's lifetime. In addition, there is reduction in the initial investment cost of US$14.2 million due to the exclusion of the GE LM2500 gas turbine at project implementation, which appears to raise the prospect of economic viability of the proposed system.

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