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CO_2 capture from flue gases: a possibility to reduce the CO_2 footprint in offshore oil installations

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Abstract:

The production of oil and gas in offshore units (FPSO) requires that all utilities (electricity, mechanical drive, hot fluids for heating and cooling water) must be available in the amount necessary at each operating condition. Lack or surplus of utilities are not allowed. Every production equipment is always sized for the highest demand condition, and then it operates at partial loads most of the time. The entire production of electricity, mechanical power and heating fluids depends on the fuel available in the FPSO – the natural gas produced with oil. Therefore, a typical FPSO has a strong carbon footprint associated with burning fuel. Carbon sequestration in an FPSO is facilitated by the possibility of re-injecting CO_2 into the reservoir, contributing to oil recovery. This work analyzes two possibilities for reducing the carbon footprint in a typical Brazilian FPSO: a) the use of a combined cycle for electrical generation, reducing fuel consumption and consequently the carbon footprint and b) the association of an amine absorption system to capture CO_2 from gas turbine exhaust gases. The analysis is performed for different oil and gas production conditions, and all systems are analyzed operating at partial loads. The combined cycle alone is capable of reducing CO_2 emissions by up to 20%. The CO_2 capture system, together with the combined cycle, achieves impressive results, with a reduction in CO_2 emissions of around 50% during the entire life of the platform. Problems of space and weight of the equipment are also discussed in the work.

Keywords:

Offshore oil and gas production; FPSO; Carbon capture and storage - CCS; Exergy, CO_2 footprint reduction.

1. Introduction

Due to environmental concerns, there is a need to decrease the carbon footprint in every energy-intensive industrial operations. In many cases, the use of renewable energy is possible. However, the production of oil and gas in offshore units (FPSO) far from coast and in deep waters requires utilities such as electric power, mechanical power and hot fluids for heating processes that depend on the use of fossil fuels, especially natural gas. If the fuel is fossil, the CO2 emissions can be reduce by two strategies: increasing the power efficiency in the processes, and/or by carbon sequestration. The electric power and process heat needs in a FPSO are huge. It is usual to adopt waste heat recovery from exhaust gases to supply hot fluid utilities - that is, cogeneration.

The prime movers to electric generators usually are gas turbines. To increase the low efficiency of gas turbines it is common the adoption of combined cycles. This is largely adopted in electric power generation onshore and is a mature technology. However, the available space and allowed weight in a FPSO is a challenge to adopt this technology. Nord et al [1] presented studies for the installation of combined cycle in offshore oil platforms in the North Sea. Again, Nord et al [2] made an optimization of the combined cycle under restrictions of power and weight for offshore oil production. Vidoza et al [3] explored the concept of "Power Island" to produce electricity to various FPSO's simultaneously, using different combinations of combined cycle groups in a dedicated platform (the "power island"). All results described above showed the direct link of the fuel consumption (efficiency of the system) and the reduction in CO_2 emissions.

The other way to reduce CO_2 emissions is the Carbon Capture and Storage (CCS). The IPCC presented a special report [4] dealing with this option and discussing the technologies to obtain this desired effect, as an option in the portfolio of mitigation actions to stabilize GHG concentrations in the atmosphere. CCS presents two challenges: the transportation from the carbon capture location to the final destination, and the geological stability of the storage location. Offshore oil fields can be interesting to store CO_2, since the injection of CO2 is one of the EOR (enhanced oil recovery) technologies, and the geological structures associated to oil fields

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are stable. Risks and costs associated with CO_2 transportation are avoided if the capture is made in the FPSO. Some studies [5-6] present strategies to capture CO_2 in offshore oil production.

Leung et al [7] presented a review on the different technologies and paths to CCS. For post-combustion separation, the CO_2 concentration in the gas mixture is a strong factor to induce the choice of a suitable separation process. Songolzadeh et al [8] indicate that cryogenic distillation and membrane processes are efficient for gas streams with high CO_2 concentration. However, absorption processes may be the best choice for CO2 separation in flue gases, since the gas stream have high temperature, low pressure and low CO2 concentrations.

Petrakopoulou [9] analyzed eight power plant concepts using CO2 capture technologies, both before and after the combustion, which are assessed based on efficiency, economic feasibility and environmental footprint. In the same direction, Madejski et al [10] discusses the CCS technologies and points to the oxyfuel combustion method as a promising solution due to its smaller energy penalty. However, this is not yet a proven technology.

The use of CCS from flue gases for diesel powered ships was proposed by Long et al [11]. An absorption process was optimized and the CO_2 sequestered must be stored in the ship in liquid phase until its final destination. The energy in the flue gases is used to drive the absorption process. Einbu at al [12] presented a similar study, but destined for future liquid CO_2 ships (transport phase of CCS).

The combination of combined cycle with CCS is being studied as a solution to reduce the carbon footprint in offshore oil and gas production. Øi et al [13] presented a study to optimize costs and weight for an absorption process in offshore operations. They suggest the dimensions for the system, as well as the design capture efficiency, fixed in 87%. Nord et al [14] also presented a study for a specific oil field in the North Sea. They defined a design capture efficiency of 90%, using MEA absorption process. Dimensions and weight of the system are also presented.

New separation methods are being proposed. The study of Hammera et al [15] describes the use of supersonic separation process to reduce the carbon footprint from gas turbines. A supersonic nozzle causes an expansion of the gases, and the temperature falls below the solidification point of CO_2, which is then separated from the gaseous stream. However, this method is not yet proven and requires the compression of exhaust gases, which is an energy penalty for the process. Liu et al [16] discusses the chemical absorption technology using rotating packed bed (RPB) instead of vertical static tower. This technology is also called “supergravity” separation, since the mass and energy transfers in the absorption phase are increased as compared with the conventional effect of gravity in the absorption tower.

Sukor et al [17] presents a study dealing with CO_2 separation from the natural gas in a Malaysian gas field, reducing the CO_2 content in the natural gas to acceptable levels. It is important to say that the current Brazilian Pre-Salt FPSO’s already processes natural gas currents and injects the CO2 rich current in the oil field. The world’s first project to implement offshore CO2-EOR was launched in 2011(in the so-called Lula-pilot oil field) and a second one in 2013 (Lula-NE oil field).

Although various studies presented results for combined cycle and CCS in offshore oil production, they are centered in the design and optimization of these systems. The design conditions must deal with the maximum electric power and maximum process heat. For absorption systems (CCS), with the maximum gas flow. However, most part of the time the FPSO operates at partial loads. Ortiz et al [6] presented a study dealing with partial load for the system, following the oil and gas production curve along the time, for a Brazilian oil field.

In this paper, the work of Ortiz et al [6] is revisited, with important changes in the FPSO configuration. One gas turbine acting as a mechanical prime mover is eliminated from the system, increasing the electrical power need, reducing CO_2 emission and liberating space for the steam turbine. This allows for a better combined cycle efficiency. A MEA absorption system can also be incorporated. Part of the steam generated in the HRSG is used as energy source for the separation process. The CO_2 stream coming from exhaust gases is injected in the oil field with the CO_2 stream coming from natural gas separation. This work presents the performance of the system in partial loads, according to the oil and gas production curve. It is important to note that the system to inject CO_2 in the oil field is standard for Pre-Salt FPSO’s. The changes made in the FPSO processes and the analyzed system are described in the Section 3.

2. The FPSO characterization and production curve

The FPSO design adopted for Pre-Salt oil fields is almost standardized. The maximum capacity is 150,000 bpd of crude oil separation. The associated gas is treated until a maximum capacity of 6 MMm^3/day. The FPSO has a capacity to store 1.67 MMb - near 10 days of production. A tanker ship is sent to FPSO each week to bring the oil to onshore refineries. In some cases, the natural gas, after a rough treatment, is delivered to shore by gas ducts.

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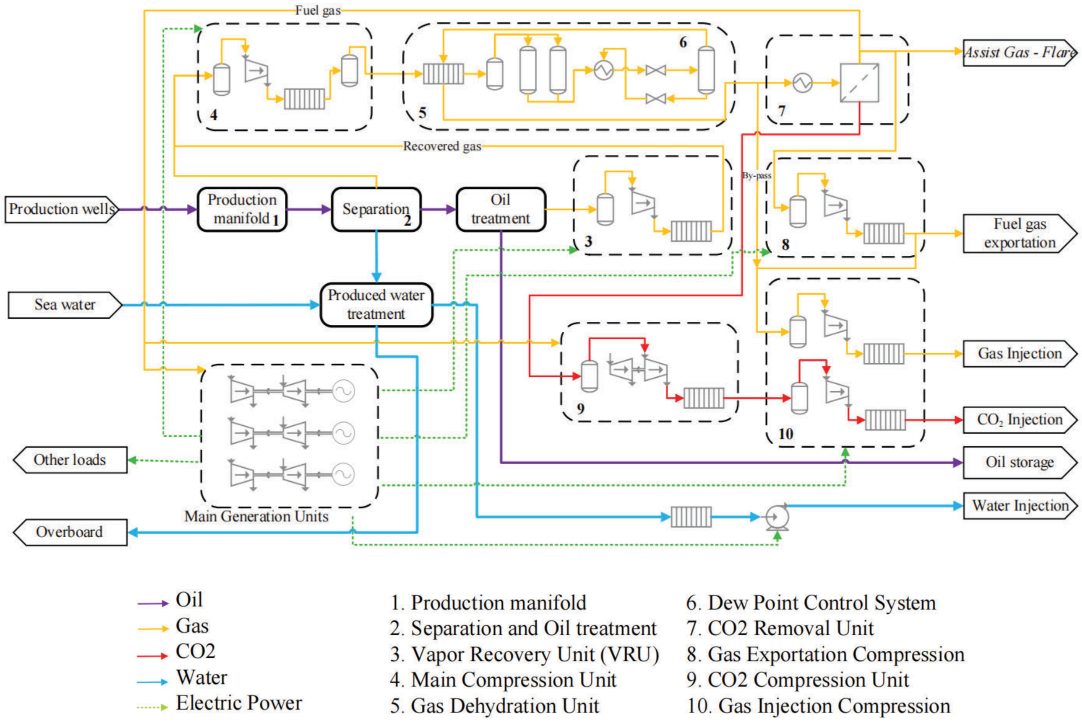

Figure 1. Topside processes in a typical Pre-Salt FPSO. Source: Ortiz et al. [18]

Due to the characteristics of the natural gas obtained, a membrane separation system is adopted to remove excess CO_2 from the natural gas, and the CO_2 rich stream is injected in the oil field. There is also compression systems to deliver the gas to the shore by gas ducts, and to inject natural gas or CO_2 rich streams in the oil field. Figure 1 shows schematically the FPSO topside processes. The electric power generation adopts three gas turbines, and another gas turbine acts as a mechanical driver for the CO_2 stream compression (subsystem 9 in the Fig.1). The exhaust gases from gas turbines generates pressurized hot water in closed circuit, which is the heat utility in the separation process. It is important to say that the FPSO already presents CO_2 capture (from natural gas). The compression equipment is present and CO_2 injection in the oil field is already made.

The oil and gas production of a FPSO is not constant. A typical production curve is presented in the Fig.2. The lifetime of an oil field is in the order of 25 years, and the FPSO is designed to stay anchored all this time. The topside processes are also designed for the entire production period. Therefore, the subsystems in the topside operate almost all the time in partial load, since they were designed for the critical condition for each one.

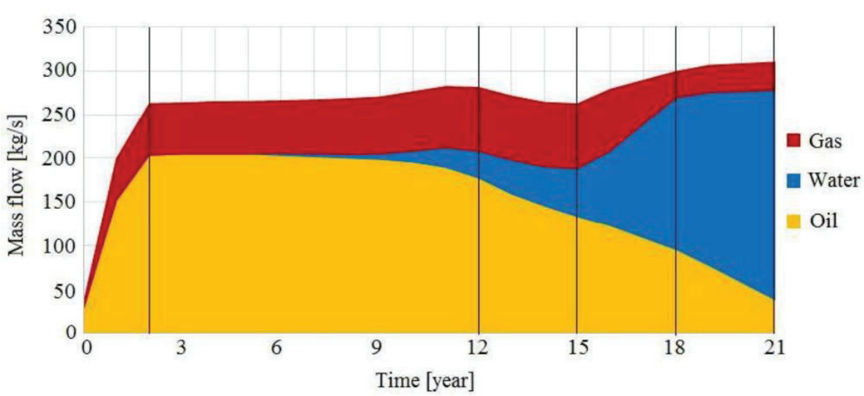

Figure 2. Typical crude oil production curve. Source: Ortiz et al [6]

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Table 1. Operating points of the FPSO analyzed in this work. Source: Ortiz et al. [6]

Operating point	Oil production year	Electricity demand [kW]	Platform electric load [77MW max.]	Hot water demand [kg/s]
1	Year 2	72120	93,7	431.1
2	Year 12	73140	95,0	413.7
3	Year 15	70650	91,8	390.2
4	Year 18	48960	63,6	307.2
5	Year 21	46020	59,8	268.7

Table 1 indicates some important points in the oil production curve. The first condition is when the maximum oil and gas production is reached, in the second year of operation. Point 2 presents the maximum liquid capacity. Point 3 indicates a decreasing oil production in the year 15. Point 4 is related to the 50% BWS (basic sediment and water) and point 5 to the condition of maximum BSW. The values were obtained from a comprehensive FPSO operation simulation for each operation point presented in [6].

3. Alternatives to reduce CO_2 footprint from exhaust gases

This paper proposes modifications in the FPSO subsystems to reduce the CO_2 footprint: a) eliminating the mechanical drive gas turbine, substituting it by electric motors; b) introducing a HRSG before the hot water heaters; c) to adopt a steam turbine working in combined cycle; and d) introducing a MEA absorption system to capture CO_2 from flue gases. Captured CO_2 is sent to the already present CO_2 injection system.

The elimination of the mechanical drive gas turbine liberates space to the steam turbine installation and increases the electricity demand. However, the combined cycle can generate this additional demand with greater efficiency. The combined cycle is not designed to maximum power production, since there is no demand for extra power, and the hot water needs must be preserved. Part of the steam is diverted to water heaters, complementing the hot water heaters driven by exhaust gases coming from HRSG. When a CO_2 absorption system is added, more steam is diverted from steam turbine to drive this process. Figure 3 shows the proposed modifications.

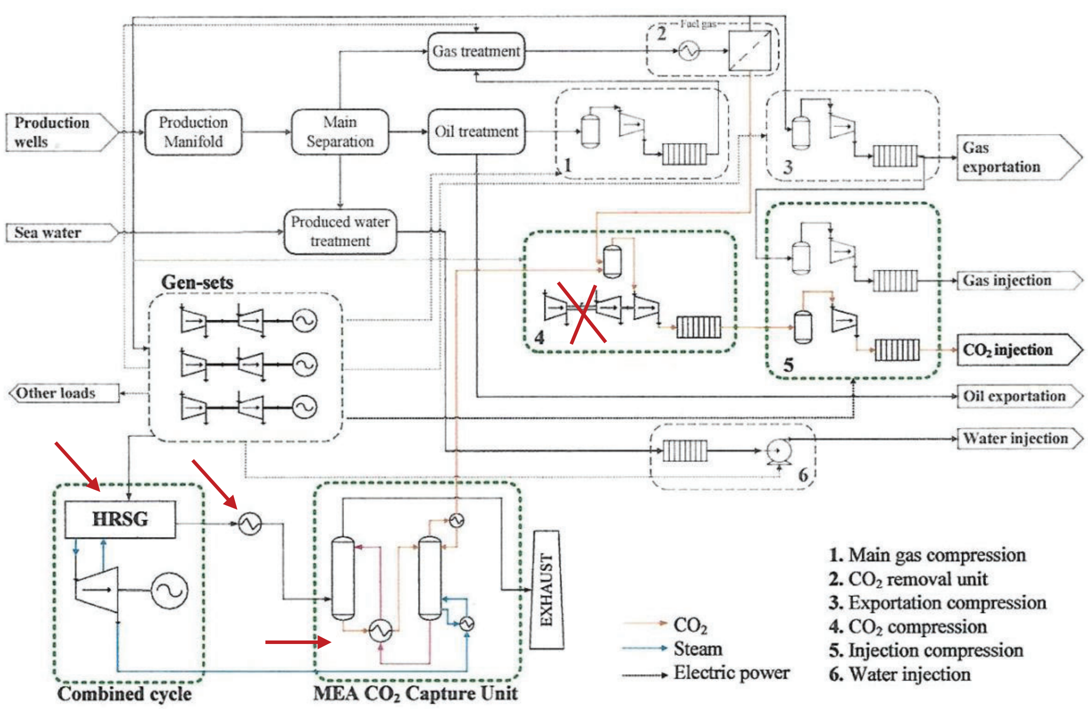

Figure 3. Proposed modifications in the FPSO topside processes. Source: Ortiz [6] modified.

4. Methodology of analysis

The methodology used was based on the mass and energy balances for each equipment or FPSO subsystem and for the process as a whole.

All equipment operate in partial loads, as mentioned before. So, for pumps and gas compressors, the performance curves were parameterized as a function of its load whenever available. Typical adimensional curves were adopted when true performance curves were not known.

Power from gas turbines were modeled first in Thermoflex® software to determine the fuel consumption, exhaust gas temperature and compositions, and energy efficiency as a function of load. This is possible since this software package has the gas turbines performance in the databank (GE-LM2500 for power generation, GE-LM2000 for mechanical drive). An adequate steam turbine was chosen to the steam cycle. Its isentropic efficiency was parameterized as a function of steam mass flow.

The whole processing and utilities subsystems were modeled in Aspen Hysys® software for complete properties and performance calculation. The HRSG and all other heat transfer equipment were modeled adopting the (ε - NTU) method for conditions off-design.

The CCS technology to reduce the CO_2 emissions from flue gases was simulated with Monoethanolamine (MEA) package, with a capture efficiency of 85%. The chemical absorption unit was modeled using the thermodynamic package Acid Gas module in Aspen Hysys software. This subsystem was installed downstream of the cogeneration heat exchangers for hot water. A compression stage for the separated CO_2, which raises the pressure from the atmospheric level to 4 bar, was also introduced since this is the suction pressure of the associated CO_2 booster compressor.

The total CO_2 emissions from flue gases were determined for five FPSO operating points and for three configurations: a) base case - the FPSO as it is today; b) removing the mechanical drive gas turbine and adopting a combined cycle; and c) the combined cycle with CCS as described above. In this way, it was possible to compare the base case with the effect of a combined cycle, and the effect of a combined cycle with CCS on the CO2 emissions.

4.1. Steam cycle characteristics

The combined cycle is composed by the three gas turbines adopted to generate electric power (GE-LM2500), each with its own HRSG and a single steam turbine. The vertical HRSG has one pressure level for steam generation, due to weight and area restrictions. Table 2 presents the design values for the HRSG. After passing the HRSG the flue gases passes through the hot water heaters. The steam turbine is an extraction-condensation with controlled extraction at 4 bar and condensation at 0.07 bar.

Table 2. HRSG design characteristics

Steam pressure [bar]	38.5
Steam temperature [^oC]	480
Pinch point temperature difference [^oC]	25
Approach temperature [^oC]	5
Pressure loss gas side [kPa]	3.5

4.2. Absorption system characteristics

The modeled absorption system is presented in the Fig.4. This is a typical MEA absorption system. In the model developed, some simplifications were assumed: the water wash in the absorber and the reclaimer part in the bottom of the stripper were eliminated. The solvent was assumed to stay inside the system, and do not need substitution. As mentioned before, the CO_2 flow exiting the absorption module are at atmospheric pressure and needs to be compressed to 4 bar. This compressor is not present in the Fig.4, but its power needs were considered in the complete simulation.

The design point for the CO_2 absorption system resulted in a preliminary size as given in the Table 3. It is important to mention that the absorber and the stripper columns are vertical, and the floor area is calculated. The columns are of the type with plates and barriers. Other geometries can be attempted to reduce weight and size.

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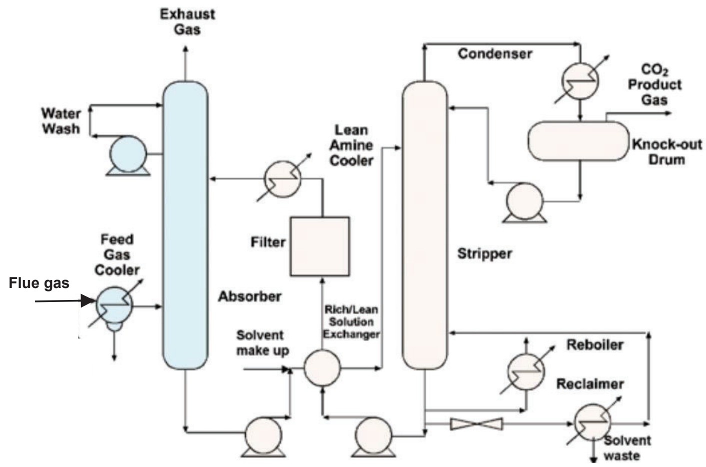

Figure 4. MEA absorption process characteristics. Source: IPCC [2005]

Table 3. Preliminary design for the MEA absorption system.

Dimensions	Absorption tower	Stripper tower
Diameter [m]	6.0	3.1
Height [m]	29.0	7.3
Number of plates	24	11
Plate spacing [m]	1.2	0.9
Barrier height [m]	0.18	0.14
Floor area [m^2]	28.3	7.3

Øi et al [13] suggested conditions for an offshore application with 87 % capture efficiency, with 13 m absorber packing height (plus distribution and collecting height) and 15°C minimum approach temperature due to a decrease in equipment cost, size and weight. Nord [14] presents a design with a diameter of 13.6 m and packing height of 18.6 m for the absorber (plus distribution and collecting height). For the stripper, 3 m diameter and 7 m packing height.

4.3. Definition of efficiency calculation

In the next section are presented the obtained values for different efficiencies types. This section presents the definition adopted for each one of them.

Equation (1) presents the definition of electric power generation efficiency:

$$\eta_{\mathrm{elect}} = \frac{\dot{W}_{\mathrm{elect}}}{\dot{m}_{\mathrm{fuel}} \mathrm{LHV}} \tag{1}$$

The cogeneration system can be evaluated by a first-Law efficiency, taking into account each useful energy flow produced in each configuration as presented in the Eq. (2). In the base case, for example, there is mechanical power produced, but no reboiler heat. In the CC and CC+CCS configurations, there is no mechanical power produced. It is important to observe that the hot water heat is the same for each FPSO operating point, for every configuration.

$$\eta_{\mathrm{cogen}} = \frac{\dot{W}_{\mathrm{elect}} + \dot{W}_{\mathrm{mech}} + \dot{Q}_{\mathrm{hot\ water}} + \dot{Q}_{\mathrm{reboiler}}}{\dot{m}_{\mathrm{fuel}}\ \mathrm{LHV}} \tag{2}$$

The definition for the second Law efficiency is shown in the Eq. (3) and is similar to the first-Law, but dealing with exergy flows, instead of energy flows:

$$\varepsilon_{\mathrm{cogen}} = \frac{\dot{W}_{\mathrm{elect}} + \dot{W}_{\mathrm{mech}} + \dot{B}_{\mathrm{hot\ water}} + \dot{B}_{\mathrm{reboiler}}}{\dot{m}_{\mathrm{fuel}}\ b_{\mathrm{fuel}}^{\mathrm{ch}}} \tag{3}$$

The same observations made for the first Law efficiency applies in Eq. (3).

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5. Results and discussion

The results obtained for each FPSO configuration are discussed in this section. Comparisons among the configuration are also presented.

5.1. The base case results - current FPSO configuration

The results for the base case are presented in the Table 4. The conditions 1 to 5 are those already defined in the Table 1. All electrical and mechanical power, as well as the hot water generation are those strictly necessary to the FPSO operation. The CO_2 compressor (CO_2 from natural gas processing) uses a gas turbine as prime mover. The total CO_2 emission from all exhaust gases is the main parameter for comparison purposes.

Table 4. FPSO power generation and CO_2 emission in the base case configuration.

Parameters	***FPSO operation condition***				
	1	**2**	**3**	**4**	**5**
Number of gas turbines (GT) for electricity power	3	3	3	2	2
GT Electrical power produced [MW]	72.12	73.14	70.65	48.96	46.02
GT - electrical power - load [%]	93.7	95.0	91.8	95.4	89.6
Electric power efficiency (LHV based) [%]	36.82	35.77	35.51	36.06	35.56
Number of gas turbines for mechanical power	1	1	1	1	1
GT mechanical power - for CO_2 compressor [MW]	12.21	15.15	14.22	7.00	6.87
GT mech. power load [%]	76.3	94.7	88.9	46.6	42.9
Total fuel consumption - all GT [kg/s]	5.03	5.50	5.41	3.43	3.30
Total CO_2 emission - all GT [Mt/year]	0.432	0.471	0.462	0.293	0.280

The electric power produced for each operation condition are the same as present in the Table 1 and were obtained from a detailed mass and energy balance for the topside processes and general electric loads (illumination, air conditioning, etc.). To compress the CO_2-rich stream separated from the natural gas, a dedicated gas turbine is employed and the mechanical power needed can be seen in the Table 4. The total fuel consumption is the sum of the needs of electric power gas turbines and the needs for the mechanical drive turbine. The total CO_2 emission is calculated from the total fuel consumption.

5.2. Combined cycle configuration results

The first approach to reduce the CO_2 footprint from the prime movers is the elimination of the mechanical power gas turbine, substituted by a steam turbine operating in Combined Cycle configuration with the gas turbines. Oil and gas production are maintained at operation conditions 1 to 5, as in the base case. The hot water need for heating purposes is also verified.

Figure 5 shows the temperature profiles for exhaust gases and the steam generator for operational condition 3, which produces the maximum amount of steam. It must be observed that the combined cycle was not optimized to maximize power, because the exhaust gas (still very hot) must provide the energy to produce the process hot water.

Table 5 shows the results for the combined cycle configuration. The elimination of the mechanical power gas turbine increased the electricity needs, but the combined cycle presents higher efficiency for power generation. The net effect is a reduction in the total CO_2 emission. In the operation conditions 4 and 5, the electric power is substantially reduced and one gas turbine must be deactivated. This reduces the steam mass flow for the combined cycle. The steam needs to water heaters contributes to reduce the power from the steam turbine, and the reduction in the CO_2 emissions are low.

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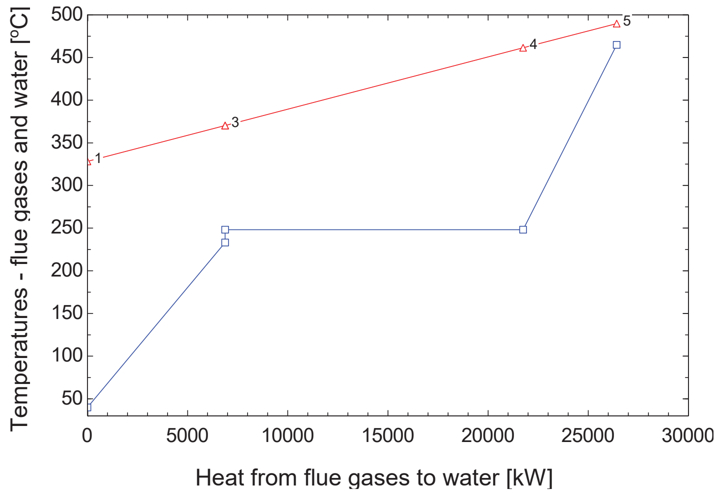

Figure 5. Temperature profiles in the HRSG. Operational condition 3

Table 5. FPSO power generation and CO_2 emission in the Combined Cycle configuration.

Parameters	FPSO operation condition				
	1	**2**	**3**	**4**	**5**
Number of gas turbines (GT) for electricity power	3	3	3	2	2
GT Electrical power produced [MW]	68.47	72.32	69.70	49.85	45.79
GT - electrical power - load [%]	84.15	89.00	85.70	92.08	84.41
Steam turbine [MW]	15.87	17.05	17.27	6.17	7.15
Electric power efficiency (LHV based) [%]	45.82	46.54	46.62	42.61	43.04
Total fuel consumption - all GT [kg/s]	4.04	4.23	4.12	2.90	2.73
Electric power for CO_2 compression [MW]	12.21	15.15	14.22	7.00	6.87
Total CO_2 emission - all GT [Mt/year]	0.347	0.362	0.352	0.248	0.231

5.3. Combined cycle with exhaust gas CCS

To reduce even more the exhaust gases CO_2 footprint, a third configuration was analyzed: a Combined Cycle with CCS. In this configuration, there is a carbon capture from the exhaust gases by a MEA system, with efficiency in the range 0.75 to 0.80.

The CO_2 separated from the exhaust gases and the CO_2 stream coming from the natural gas treatment are both re-injected in the oil field, after mixing and compression to adequate pressure. Table 6 presents the results.

Although the electricity production efficiency is reduced, the total CO_2 emission drops sharply, due to the sequestration of the CO_2 from exhaust gases. The electric power need for CO_2 compressors increases, due to the increased mass flow in the CO_2 compressors. To operate the separation, there is also a thermal energy utilization in the reboiler of the stripper, to liberate the CO_2 from the rich amine solution.

It is interesting to note that the steam turbine power must be derated when compared with the Combined Cycle configuration, since part of the steam flow must be diverted to supply the heat for the sequestration process. Øi et al [13] estimates the heat consumption to be approximately 5.5 MJ/kg CO2 removed. Nord et al [14] evaluated the specific reboiler duty for the process to be 3.6 MJ/kg CO2. Obtained values in this work are of the same order of magnitude.

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Table 6. FPSO power generation and CO_2 emission in the Combined Cycle with carbon capture and sequestration (CCS) configuration.

Parameters	**FPSO operation condition**				
	1	**2**	**3**	**4**	**5**
Number of gas turbines (GT) for electricity power	3	3	3	2	2
GT Electrical power produced [MW]	79.65	80.68	79.56	52.72	48.75
GT - electrical power - load [%]	98.21	99.50	98.10	97.50	90.00
Steam turbine [MW]	9.13	11.26	10.16	3.88	5.07
Electric power efficiency (LHV based) [%]	42.80	43.86	43.30	41.37	41.54
Total fuel consumption - all GT [kg/s]	4.55	4.61	4.58	3.02	2.86
Electric power for CO_2 compression [MW]	16.05	17.86	18.35	7.36	7.30
Thermal energy in the CCS / CO_2 captured [MJ/kg]	4.198	3.917	4.155	3.918	3.891
Total CO_2 emission - all GT [Mt/year]	0.185	0.216	0.183	0.209	0.184
Total CO_2 captured by CCS system [Mt/year]	0.206	0.179	0.208	0.049	0.059
CCS system CO_2 capture efficiency [%]	77.59	73.12	76.08	79.21	76.88

5.4. Configurations comparisons

Figure 6 shows the electric power generation efficiency for each configuration, for the different operation conditions of the FPSO. The reduction of the efficiency observed for the CC+CCS configuration is due to the power derating of the steam turbine. The values obtained to CC and CC+CCS are far below traditional combined cycles designed to exclusive power generation because part of the exhaust gas energy must be allocated to generate hot water for FPSO processes, which is a priority.

The Figure 7 presents the first and second-Law efficiencies for each configuration and as a function of the year of FPSO operational phase for the cogeneration system. As usual, first-Law efficiencies are higher than second-Law ones when the driving force is a fuel. Apart from this, the exergy of a heat flow is smaller than the energy flow. It is interesting to note that the higher efficiencies occur for the CC configuration. When a CCS system is adopted, there is a need of extra power to compress the separated CO_2, and the cogeneration efficiency decreases.

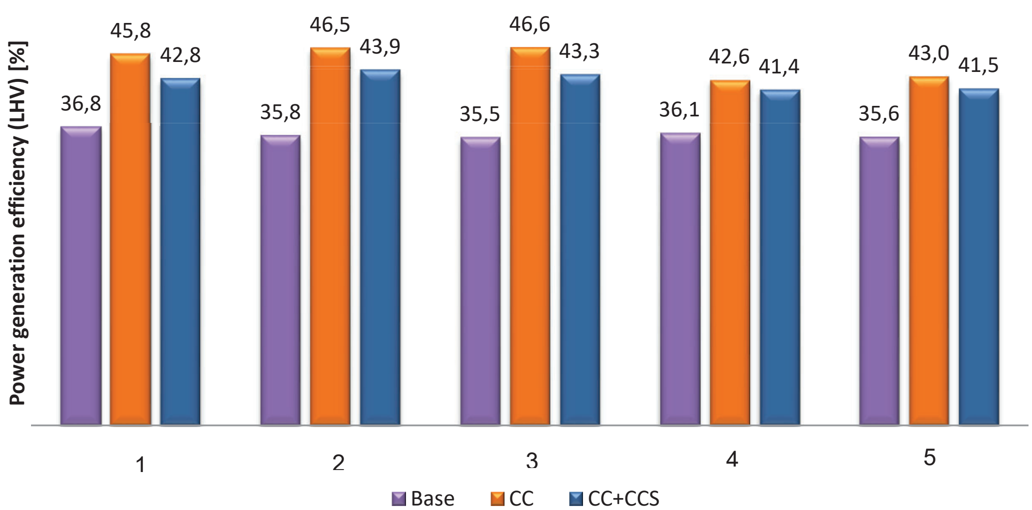

Figure 6. Electric power generation efficiency (LHV based) for different FPSO operation conditions.

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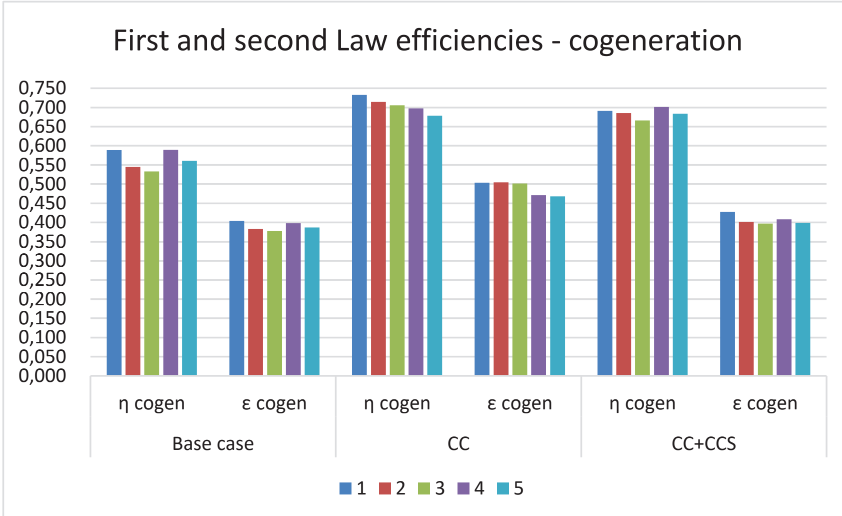

Figure 7. Efficiencies for the three configurations.

The reduction in the CO_2 emissions can be seen in the Fig.8. The reduction in the emissions are greater for the conditions which uses three gas turbines. With only two gas turbines operating, the derating of the steam turbine is high due to less available steam flow and hot water needs, and the benefits are not so evident. Fortunately, condition 4 occurs after 18 years of operation of the FPSO and condition 5 occurs after 21 years, near the end of the oil field lifespan.

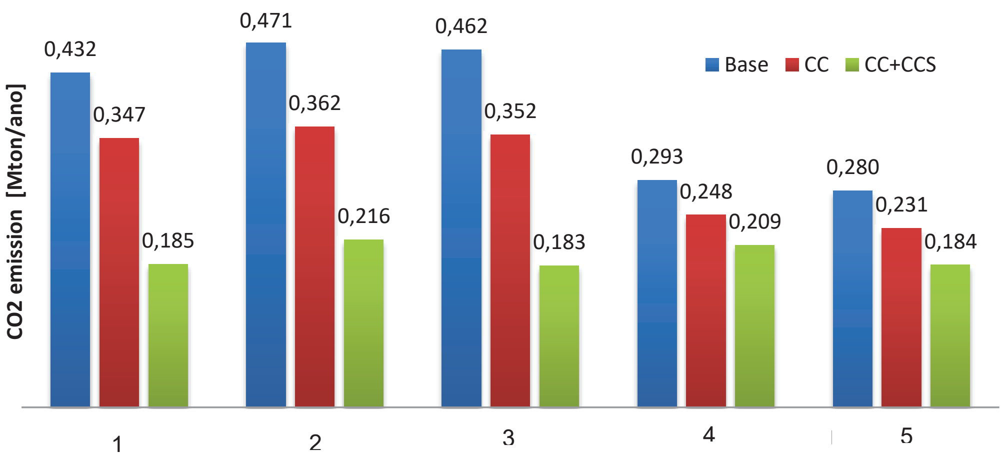

Figure 8. CO_2 emissions for different FPSO operating conditions

To make a comprehensive view of the CO_2 footprint reduction, Table 7 presents the CO_2 emission reduction as a percentage of the base case. The last column is the weighted average reduction for the analyzed period, considering the 21 years. Is to be noted that till the operation year 18, the reduction in the CO_2 emission is higher than 20% for the Combined Cycle configuration (CC) and higher than 50% for the Combined Cycle with CCS configuration (CC+CCS).

Table 7. CO_2 emission percentual reduction compared to Base Case

Configurations	FPSO operation condition					
	1	2	3	4	5	Average
CC to Base case	19,6%	23,1%	23,8%	15,3%	17,3%	21,6%
CC+CCS to Base case	57,2%	54,1%	60,5%	28,6%	34,3%	50,1%

Both alternative configurations presents interesting results. With the Combined Cycle configuration, the CO_2 footprint from exhaust gases is reduced by 20%, while the Combined Cycle with CCS reduced the CO2 emission by 50%. Only near the end of the FPSO lifetime the reduction is smaller, due the fact that only two gas turbines are operating and the hot water for FPSO processes does not reduces proportionally.

6. Concluding remarks

The results obtained in this work are of a prospective nature for new FPSO's, showing the order of magnitude of attainable CO2 footprint reductions. The proposed changes are not feasible for the operating FPSO.

The combined cycle configuration was not optimized for maximum power production, since electric power surplus is not allowed. In the same sense, the combined cycle is not optimized for maximum efficiency, since a compact system with a weight as low as possible is desirable. Apart from this, the need of hot water as an utility to the processes in the FPSO also puts a limitation to the maximum efficiency. Even with these limitations, a combined cycle proved to obtain 20% reductions in the CO_2 emissions.

The configuration with a combined cycle with Carbon Capture and Storage from flue gases can obtain near 50% CO_2 emissions reduction - an impressive figure. The proposed absorption system is a proven technology. The evaluation of the rotating packing bed (RPB) technology, instead of the usual gravitational packing bed, must offer a better weight and space solution for absorption systems. Other technologies, especially in the family of oxi-fuel combustion, may present even better results, provided they become mature.

Whatever the solution chosen, the topside processes in the new FPSO designs must be optimized for weight and size to accommodate the new subsystems.

Nomenclature

	Variables		**Acronyms and abbreviations**
$\dot{B}$	Exergy flow [kW]	BSW	Basic sediment and water
b	Specific exergy [kJ/kg]	bpd	Barrels per day
$\dot{m}$	Mass flow [kg/s]	CC	Combined-cycle configuration
$\dot{Q}$	Heat flow [kW]	CC+CCS	CC with Carbon Capture and Sequestration
$\dot{W}$	Power [kW]	EOR	Enhanced oil recovery technology
LHV	Lower heating value [kJ/kg]	FPSO	Floating production storage and offloading facility
		HRSG	Heat Recovery Steam Generator
η	First-Law efficiency	MMb	Millions of barrels
ε	Second-Law efficiency	ε - NTU	Method to evaluate partial load in heat exchangers

	Subscripts		**Superscripts**
elect	Electric	*ch*	Chemical
mech	Mechanical		
hot water	Hot water for processes		
reboiler	Steam to drive the stripper		
fuel	Natural gas used as fuel		
cogen	Cogeneration system		

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