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OPTIMAL CONFIGURATION OF A FLOATING COMBINED CYCLE POWER PLANT FOR OFFSHORE APPLICATIONS

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Abstract. Recent studies have proposed the integration of combined cycles in offshore oil platforms, in order to increase their efficiency. Offshore oil platforms are usually energized by gas turbines, which are operated at very low loads. Operating at low loads is inefficient and more energy intensive. Current environmental trends are also aiming to reduce CO_2 emissions in offshore oil and gas industry. This study proposes an analysis of a floating power plant that would supply electricity for three FPSOs (Floating Production Storage and Offloading) in the Brazilian Pre-salt. Genetic algorithms are applied to determine optimum combined cycle configurations, according to three main objectives: minimization of weight-to-power ratio (WTP), minimization of fuel consumption during complete operational lifetime (FCOM) and minimization of specific costs (COSTS). Layouts and specifications were obtained for the combined cycles. Installed capacity varies between 200 and 300 MW, and purchased-equipment costs between 100 and 200 MMUSD. In the three cases there was an important reduction of CO_2 emissions, between 16% and 25% reduction with respect to the case without floating power hub.

Keywords: Efficiency, Combined Cycle, Offshore, Oil and Gas

1. INTRODUCTION

Current concerns with resources availability has promoted electrification projects and networks expansion in the last decades, allowing the distribution of renewable and less polluting energies sources. The Power Island or Floating Power Hub is an application of the Gas-To-Wire (GTW) concept, which promotes energy production directly at the gas extraction fields. The floating power hub is specifically applicable in offshore oil and gas fields.

Reinjection and burning of associated gases in oil extraction platforms is still frequent, mainly due to high costs of transformation and use of this type of resource at sea. However, low efficiency related to the use of associated gas in maritime operations, and the increasing concerns for greenhouse gas (GHG) emissions has driven the research on efficiency processes offshore. The GTW application aims to transform the gas extracted from the marine wells and turns it directly into electricity, which could be easier to transport, depending on the seabed and basin characteristics.

Power islands could be applied in offshore oil fields such as the Gulf of Mexico, the Presalt in Brazil, the North Sea, and the Australian coast. The companies, SEVAN, Siemens and Das Norske Veritas (DNV) proposed concepts of this type of power plant, based on existing gas and steam turbines for shore applications, in Hetland et al (2009). Other studies on offshore systems have been carried out by Nguyen et al (2014), Pierobon et al (2013), Carranza et al (2015) and Barrera et al (2015). This document proposes a methodology of design and calculation for a power island adapted to the Brazilian case. Combined cycle components and operation over time are optimized to meet three objectives. Main objectives are weight reduction, the reduction of capital costs and the reduction of fuel consumption.

2. METHODOLOGY

The methodology is based on the analysis of the combined cycle main components: Gas turbine, steam turbine, heat recovery boiler, condensate pump and condenser. The power island would be composed by several combined cycle blocks, consisting in a group of the aforementioned equipment. The first step is to determine the conformation of these combined cycle blocks. by performing an optimization programming. After obtaining the block configuration, performance indicators, such as fuel consumption and emissions, are evaluated.

Combined cycle calculation starts with an energy balance in each component. Heat recovery steam generator (HRSG) duties are determined through Pinch Point method, detailed in Ganapathy (2003). After main thermodynamic parameters are established, the components are dimensioned, obtaining values such as pipe diameters, number of tubes, among others. Weight, volume and costs are obtained from diverse correlations explained in further sections of this paper.

When sizing design is completed. Design overall heat transfer coefficients and steam turbine design parameters will be used to calculate part load performances. Part load parameters are calculated for an operating load range between 60% and 100%. Finally, the electric demand forecast allows estimating a corresponding fuel consumption and emissions throughout the whole lifecycle of the FPSO or platform. A more detailed explanation of each step of the applied methodology is given below.

2.1 Thermodynamic Model

2.1.1   Gas Turbine

Two commercial turbines were selected to carry out the combined cycle design, the internal processes of the gas turbine are considered as a black box. LM 2500 and LM 6000 both from the GE manufacturer and used for marine applications. Part load performances are shown in Fig.1. The exhaust gas and fuel consumption properties were extracted from Thermoflex ® software by Thermoflow (2017), and then parameterized according to the turbine load, creating behavioral curves for the off-design conditions. Specifically: fuel consumption mass flow, temperature of the exhaust gases, mass flow of exhaust gases, and total CO_2 emissions. Additionally, other properties which are not load dependent were considered, such as: total turbine weight, volume occupied by the equipment and cost of the turbine (including generator).
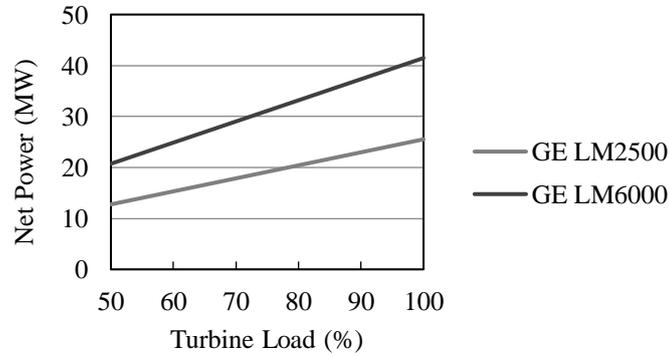

Figure 1 Part Load Performances of Gas Turbines

The combustible gas produced does not have a standard composition, instead it is a mix of gases. The heat value of such gases is considered to adapt the gas turbine performance curves, together with the climatic conditions for Rio de Janeiro. The parametrized equations are based on fourth degree polynomials. degree, as shown below:

$$m_f = (C1)_i \, w_{GT}{}^4 + (C1)_i \, w_{GT}{}^3 + (C2)_i \, w_{GT}{}^2 + (C3)_i \, w_{GT} + C4_i \tag{1}$$

$$m_g = (C1)_i \, w_{GT}{}^4 + (C1)_j \, w_{GT}{}^3 + (C2)_j \, w_{GT}{}^2 + (C3)_j \, w_{GT} + C4_j \tag{2}$$

$$T_g = (C1)_i \, w_{GT}{}^4 + (C1)_k \, w_{GT}{}^3 + (C2)_k \, w_{GT}{}^2 + (C3)_k \, w_{GT} + C4_k \tag{3}$$

$$E_g = (C1)_i \, w_{GT}{}^4 + (C1)_l \, w_{GT}{}^3 + (C2)_l \, w_{GT}{}^2 + (C3)_l \, w_{GT} + C4_l \tag{4}$$

Where m_f: Fuel mass flow, m_g: Exhaust gases mass flow, T_g: Exhaust gases temperature. E_g: CO_2 emissions. $(C1, C2, C3, C4)_{i,j,k,l}$: Constants. w_{GT}: Net power output.

2.1.2   Heat Recovery Steam Generator (HRSG)

HRSG thermodynamic design is performed according to Ganapathy (2003). Each HRSG is dimensioned separately through guidelines provided by ESCOA (2002). A single pressure level HRSG is considered in this paper, with vertical finned piping, divided in three main sections: economizer, evaporator and super heater. A generic temperature profile is shown in Figure 2, and most important dimensional variables considered are shown in Figure 3.
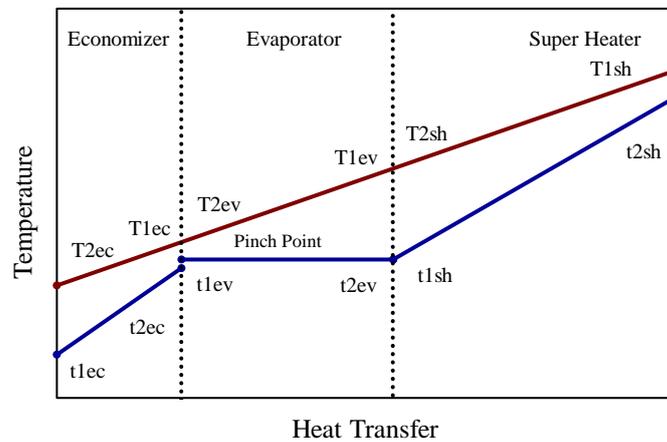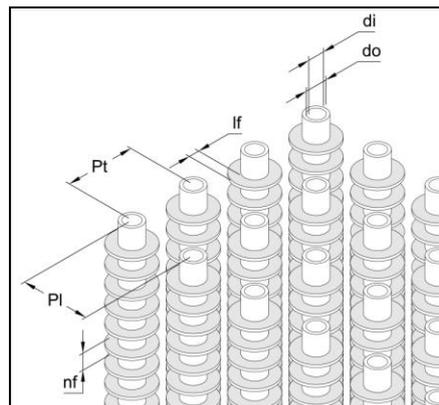
Figure 2 HRSG Temperature Profile

Figure 3 Sizing dimensions for HRSG

2.1.3   Steam Rankine Cycle

The parameters of the steam cycle are obtained through the Pinch Point analysis performed previously, because the steam turbine performance depends on the characteristics of the exhaust gases of the gas turbine. Steam flow and Steam Turbine Inlet Temperature are some of the parameters used to calculate condenser and pump capacities. A condensation turbine is considered for this combined cycle. Additionally, it is assumed that there are no significant leaks.

2.2 Dimensioning

The physical characteristics, weight and volume of the combined cycle are fundamental for estimation of size and cost of the ship or platform that will host the floating plant. Additionally, through these values, it is also possible to calculate the Weight-to-Power ratio, that is, the relation between the weight and the power produced by the combined cycle plant, which is an important indicator result evaluation.

In the case of gas turbines, the weight and volume are already pre-established, and can be extracted from the manufacturer's data, organized in Table 1. HRSGs are more complex, since this equipment is composed of several parts and structures such as pipes, casings, condensation tanks, and others. HRSG weight is mainly determined by the weight of the pipes, being the heaviest component of this equipment. For this study, HRSG weight will be estimated through the pipes and the density of the material by which they are built, Equation (5). The same considerations, in this case, are applied for estimating condenser weight, as detailed in Eq. (6). In the case of the steam turbine, the correlation of Eq. (7), presented by Rivera-Alvarez (2015), is applied. for steam turbines up to approximately 20 MW.

Table 1 Gas Turbine Sizing Data

Gas Turbine Model	Height (m)	Width (m)	Length (m)	Volume (m3)	Weight (Ton)
GE LM 2500	3,98	2,64	13,94	146,47	90,00
GE LM 6000	4,91	4,31	16,51	349,07	136,98

$$M_{HRSG} = \rho_{tubs} \sum \left[\pi \left(\frac{d_o{}^2-d_i{}^2}{4}\right) L_f N_r N_t\right]_{ec,ev,sh} + \rho_{fins} \sum \left[\pi \left(\frac{(d_o+l_f)^2-d_o{}^2}{4}\right) n_f t_f L_f N_r N_t\right]_{ec,ev,sh} \tag{5}$$

$$M_{COND} = \rho_{tubs} \left[\pi \left(\frac{d_o{}^2-d_i{}^2}{4}\right) L_f NT\right] \tag{6}$$

$$M_{ST} = 220(m_{steam})^{3/2} + 1647,5 \tag{7}$$

Finally, it is considered that total power plant weight is equal to the sum of the weight of the combined cycle blocks. The weights of additional and auxiliary equipment, such as ducts, cabling and others, are not considered, being relatively smaller in comparison with the equipment with greater volume and weight.

$$M_{Total} = TQG\ (NTR\ M_{GT} + HXI\ M_{HRSG} + M_{ST}) \tag{8}$$

TQG: Total number of combined cycle blocks, NTR: Number of gas turbines that compose each block, HXI: Index of heat recovery units, indicating the number of HRSGs per block.

2.3 Economic Model

This study will consider the capital cost as main indicator for the economic model. The costs of gas turbines are obtained through Thermoflex ® software. The following correlations are applied, for steam turbine Eq. (9), recovery boiler Eq. (10), condenser Eq. (11), condensate pumps Eq. (12) and steam cycle generator Eq. (13). Obtained in studies by Frangopoulos (1991), and updated in Carapellucci et al (2013) and Roosen et al (2003). All correlations result in dollar values (USD).

$$C_{ST} = 5075,5\ W_{ST}{}^{0,7}[1 + (0,05/1 - \eta_{ST})^3][1 + 5e^{(T_{ST\ in}-866/10,42)}] \tag{9}$$

W_{ST}: Net Power (kW), η_{ST}: Isentropic Efficiency, $T_{ST\ in}$: Live Steam Temperature (K).

$$C_{HRSG} = 5404,2\ \Sigma A + 17500,2\ \Sigma B \tag{10}$$
$$A = [0,097/(P/30) + 0,9][1 + e^{(Tstout-830/500)}][1 + e^{(Tgout-990/500)(Q/\Delta TLM)^{0,8}}]$$
$$B = [0,097/(P/30) + 0,9]m_{st} + 1948,4\ m_{gas}{}^{1,2}$$

P: Pressure (MPa), $T_{ST\ out}$: Steam outlet temperature (K), $T_{G\ out}$: Exhaust gases outlet temperature (K). Q: Duty (kW). ΔTLM: Mean Temperature (K). m_{st}: steam mass flow (kg/s). m_{gas}: Exhaust gases mass flow (kg/s).

$$C_{CD} = 248\ A_{CD} + 69\ m_{CW} \tag{11}$$

A_{CD}: Heat Transfer Area (m²), m_{CW}: Cooling water mass flow (kg/s).

$$C_{PUMP} = 940 W_p{}^{0,71}[1 + (0,2/1 - \eta_P)] \tag{12}$$

W_p: Pump required power (kW), η_P: Isentropic efficiency.

$$C_{ALT} = 4028,1\ W_{ST}^{0,58} \tag{13}$$

W_{ST}: Steam Turbine Net Power Output (kW)

Capital cost are calculated using similar indexes as in the total weight calculation, Equation (14).

$$C_{Total} = TQG \ (NTR \ C_{GT} + HXI \ C_{HRSG} + C_{ST}) \tag{14}$$

2.4 Optimization

2.4.1 Model Structure

Design processes presented above are consolidated in a single calculation structure, decision variables and dependent variables organized in vectors. The decision variables will fluctuate iteratively, within a pre-established range of values, until reaching a result that meets the established objective. There are 33 decision variables in the proposed problem. Most of the decision variables are related to HRSG diameters, lengths and other sizing parameters. Three of the decision variables are related to discrete parameters or associated with integer values. The Turbine Index represents the selection between the two turbine models presented previously. The number of gas turbines is a value ranging from one to four, and finally the HRSG index, corresponds to a binary variable, which can have values of zero and one, depending on the configuration chosen, a more detailed description is presented in the next section.

2.4.2 Selecting the System Configuration

Power island presented in the concept of SEVAN-Siemens has a capacity between 500 and 600MW, containing from two to five combined cycle blocks. However, this configuration may not be optimal or adequate for the Pre-salt case. In this study, the combined cycle (CC) block is composed by a system of one to four gas turbines, connected to one or more steam recovery boilers, which, in turn, provide steam to only one steam turbine. Therefore, the combined cycle block is delimited by the steam turbine.

To determine the composition of these blocks, discrete variables are used through the Mixed Integer Nonlinear Programming (MINLP) method, where a variable is assigned an integer value. Figure 4 shows the decisions related to this type of variables, which seek to answer the following questions:

a. Which gas turbine model is selected for the CC? Assigning (1) to GE LM2500 and (2) to GE LM6000.
b.   How many gas turbines compose the CC block? Number from 1 up to 4.
c. How many HRSGs should be connected to the gas turbines? (0) a boiler shared by all gas turbines, or (1) one boiler for each group gas turbine.

Figure 4 Block configuration

2.4.3 Objectives

Three main objectives will be analyzed for the aforementioned combined cycle calculation structure: Weight-To-Power ratio, Specific Costs and Total Lifetime Consumption. A major constraint when designing more efficient systems for offshore oil and gas platforms is the cost of providing additional space. Thus, it must be assessed whether the system is compact enough to reduce ship costs and at the same time meet energy needs. The goal in this case is the Weight-To-Power or WTP indicator, which would be the total weight of the equipment, divided by the total installed capacity. This indicator assesses how compact the system is compared to its capacity to generate power.

Specific costs are the sum of equipment costs divided by total system capacity, resulting in a value of USD / MW. This indicator is a common value for comparing plant installation costs on land, and can be used to make preliminary comparisons. In order to estimate power island economic performance in more detail, it would be necessary to consider additional aspects, which are not currently included in the scope of this study, for example: cabling and piping costs for FPSO connections, maintenance costs and operation, ship costs, reduction of consumption and use of natural gas, among others.

An important driver for designing floating power hubs is the improvement in the use of nonrenewable resources. Therefore, an important environmental indicator is the reduction of gas consumption over the power hub lifetime. The most important criteria for evaluating this objective is to examine consumption not only for the nominal load, but as a sum of all the consumption from the start-up of the power hub operations to the end of the life cycle of the oil and gas

activities. By considering an accumulative consumption, it is expected to reduce consumption, when oil and gas production demands partial loads of the combined cycles in some periods of its lifetime.

2.4.4   Considerations

Without applying a floating power hub FPSOs must be self-sufficient in terms of heat and energy requirements. As indicated in the original FPSO Presalt design. However, the application of the floating power hub concept modifies this context, and proposes the rearrangement of equipment related to heat and electricity supply. Through calculations and previous studies, it has been determined that the power island requires a heat source ranging from 46 MW to 33 MW. In this study, it is assumed that an LM2500 turbine remains inside the facilities of each FPSO, coupled to a cogeneration cycle that aims to satisfy the internal heat demand. The remaining three electric generation turbines and the carbon dioxide turbo-compressors would be withdrawn. Therefore, it is assumed that carbon dioxide compressors would be driven by electric motors, and that FPSOs could produce a limited internal capacity of approximately 25 MW.

Power hub capacity is calculated considering electricity supply to three FPSO vessels. A particular consideration for this study is that the demands of the FPSOs would be the same, however, the total demand would be conditioned to the operation start-up of each unit. The time difference of entry into operation would be two years between each unit. After integrating these aspects to the analysis, a total load curve of the floating power hub is elaborated. Figure 5 illustrates the load curve with respect to the power hub life time.
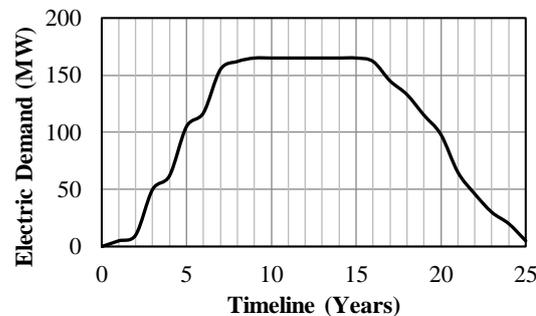
Figure 5 Load curve for the floating power hub

Once the combined calculation finishes, the obtained arrangement is used to evaluate the power hub performance over the complete platform lifetime, considering the respective partial loads. The energy dispatch considers that each generation unit starts depending on the increase in demand. Thus, the combined cycles are not operated at very low loads, and priority is given to the activation of the gas turbines.

3. RESULTS

3.1 Main Indicators

The result of the proposed algorithm is a vector of variables representing the design parameters of each optimization case. The variables are processed and organized to obtain performance indicators. A summary of the most important variables and indicators is presented in Tab. 2 and Tab. 3. The name of the objectives is simplified for comparison purposes in FCOM, COSTS and WTP, referring to fuel consumption, costs and weight / installed capacity, respectively. WTP optimization results in more compact combined cycle configurations, with fewer components and higher capacities. Although the weight is greater than the result in for costs optimization, the capacity is approximately 30% higher. Costs are heavily penalized for WTP optimization, which presents the most expensive option of the three optimization cases.

In WTP optimization the combined cycle capacity reaches almost double that needed to supply power to the FPSOs. Therefore, there would be an idle installed capacity, which, due to the large quantities of gas available, could be used to produce additional electricity. There are the options of sending additional energy to the mainland, through the installation of submerged cables, or the installation of gas liquefaction systems. The evaluation of the economic performance of these options is beyond the scope of this paper.

The results for the FCOM objective points a more efficient heat transfer design. The heat transfer area is increased, resulting in a larger volume of equipment. HRSGs occupy more volume and weight, as well as, the pinch point is the smaller in comparison with the other cases. As seen in the literature review, lower values of pinch point also affect HRSG weight and size, making FCOM optimization case the heaviest of the obtained results.

Table 2 Results: main indicators

Variables	Objectives		
	FCOM	COSTS	WTP
Gas Turbine Model	LM2500	LM2500	LM600
Ga Turbine per group	1	2	3
HRSG Index	1	1	1
Quantity of CC Blocks	6	3	2
Block Capacity (MW)	34.86	68.07	154.01
Total Capacity (MW)	209	204	308
Total Weight (Ton)	2105	1548	1780
Total Costs (MMUSD)	106.47	101.15	172.07
Fuel Consumption (kTon/Year)	**3479**	3749	3803
Specific Costs (USD/MW)	509.04	**495.29**	558.62
WTP ratio (Ton/MW)	10.07	7.58	**5.78**

Results obtained for the COSTS optimization case, were similar to FCOM objective results. Specifically, in the model and quantity of gas turbines, however, in the case of cost minimization the HRSG would be the least efficient of the analyzed cases. The pinch point of the exchanger is 29.98K, which indicates a poor performance in the heat exchange, and therefore of the general efficiency of the cycle. COSTS and FCOM specific costs differ only by 3%, this little variability in costs should be structured in the future, performing a net present value analysis including operation and maintenance costs and costs of opportunity for unused natural gas.

Table 3 Steam Cycle Characteristics

Heat Recovery Steam Generator Characteristics			
Variables	FCOM	COSTS	WTP
Height (m)	14.25	10.18	10.74
Width (m)	5.87	6.21	5.59
Length (m)	2.41	2.05	1.52
Design Pressure (MPa)	5.38	5.68	7.18
Pinch Point (K)	11.73	29.98	28.37
Steam Turbine Characteristics			
Live Steam Temperature (K)	631.03	705.77	674.44
Steam Turbine Rating (MW)	9.39	17.01	29.60

For Better visualization of equipment footprint, three conceptual illustrations were elaborated, seen in Fig. 6, which represent the different configurations in each optimization case. The three figures are on the same scale, and the components were scaled according to the results obtained to provide a better idea of the layout and volume of the set. The figures show the gas turbine as a closed package including the generator, this block is next to the respective heat recovery steam generator, and then the steam turbine and generator set (measurements obtained using Thermoflex® software), the condenser is located under the latter two components. These images were made for illustrative purposes, and construction details, pipes, connections and ducts were omitted, as well as the insulation of steam turbines that could considerably increase the volume they occupy.
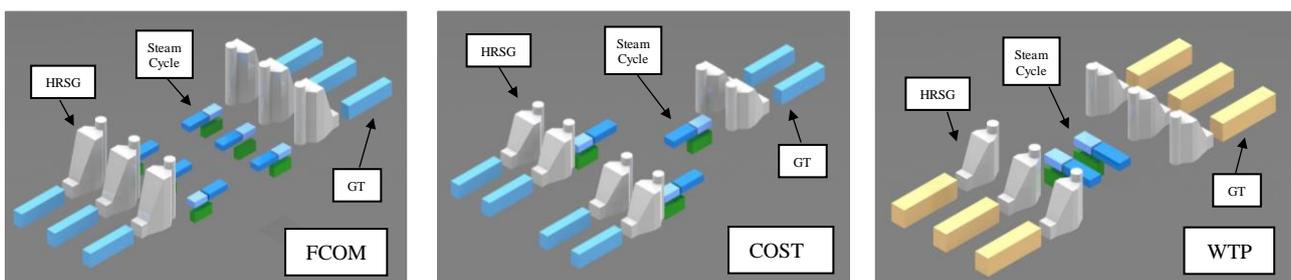

Figure 6 Approximate volumetric arrangement

3.2 Lifetime Assessment

As previously mentioned, one of the reasons of developing energy supply alternatives in oil offshore systems is the poor efficiency in which the turbines are operated during the platform lifetime. Fig. 7, Fig. 8 and Fig. 9 shown below represent the dispatch of energy in each year of operation throughout the platforms operating period. It also shows the operation input of each turbine composing the combined cycle, depending on demand requirements and on the annual fuel consumption. Each figure presents a case of optimization. The power dispatch has been programmed in a simple manner, so that each block starts operation according to demand. Within each block, the gas turbines will first start running, and the steam turbine will only start operating when the gas turbine capacity is exceeded. When there is more than one gas turbine per group, the nomenclature is given in matrix form, so that the gas turbines (GT) of the first block have the indices 11, 12, 13 ... Of the second block 21, 22, 23 ... etc.
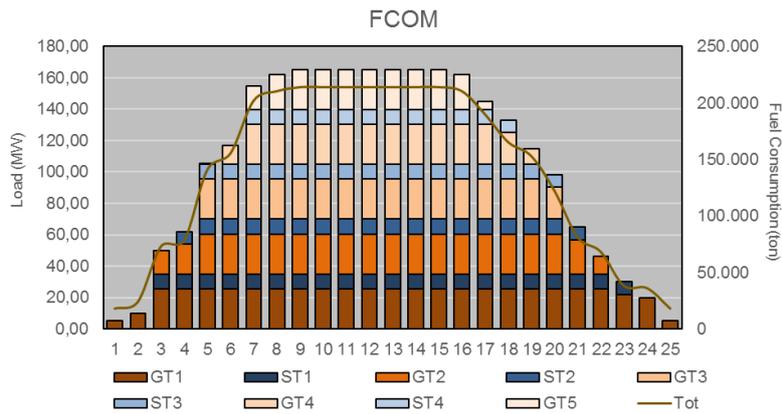
Figure 7 Combined cycle dispatch and fuel consumption (FCOM)
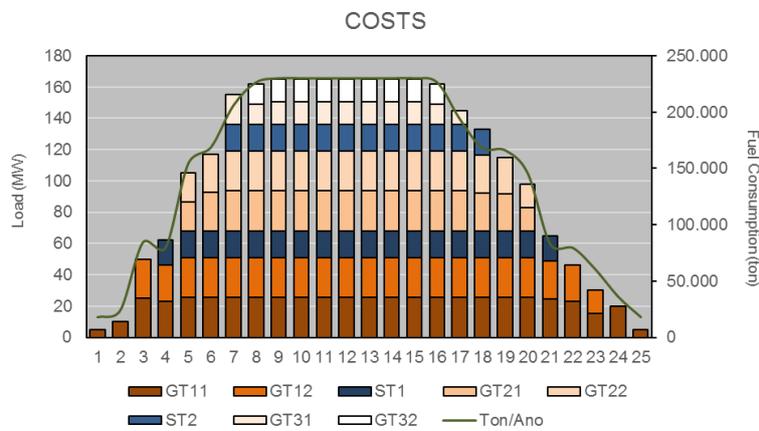
Figure 8 Combined cycle dispatch and fuel consumption (COSTS)
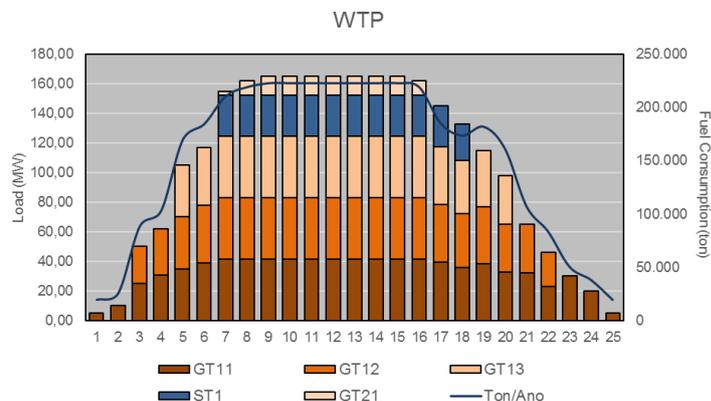
Figure 9 Combined cycle and fuel consumption (WTP)

It is observed that there is a correspondence between the consumption curves in the three cases of optimization and the load curve. The main difference is in periods when steam turbines are operating, which reduces fuel consumption. Through the forecasted turbine dispatch, carbon dioxide emissions are also calculated for the analyzed study period in each case. The consumption and emission curves are separated into two comparative graphs shown below. It should be noted that the greatest variations among the cases occur in part load operations, especially in the beginning and end years of the platforms lifetime. The most notorious fluctuations occur when the operation starts to integrate a steam turbine into the system, where both consumption and emissions fall considerably, for example, in years 18 to 22.
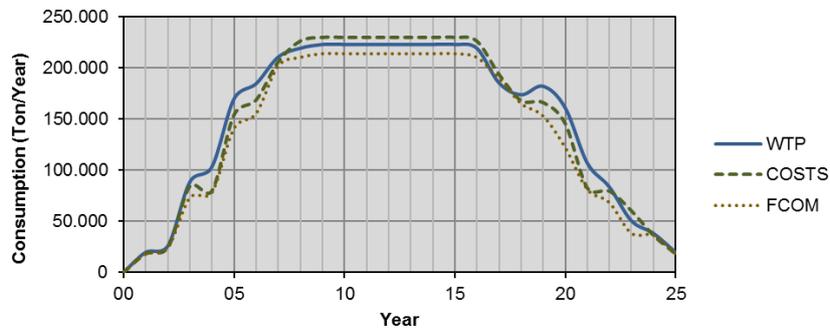
Figure 10 Comparison of fuel consumption

As expected, the curve in the case of minimizing fuel consumption presents reduced consumption values for the whole period of operation. The configuration obtained for this case is more distributed and allows the operation of more steam turbines than in other cases. The minimization of consumption confirmed the expected results, and there was a correspondence with the CO_2 emissions produced. The case of FCOM minimization results in the lowest emissions, most notably in the years between 6 and 17 of stable behavior. In this study the emissions were not selected as an objective to be minimized, therefore, there is still not specific criteria on the best configuration to reduce emissions. However, this comparison serves as a reference for future studies.

In the following table a comparison with the emissions produced in the base case is presented, that is, considering the FPSO with the initial project configuration. It should be noted that there is a considerable reduction in emissions, even in the most pessimistic case of Power Island, emission reductions are reduced by around 16% in the COSTS case, 20% in the FCOM case and 25% in the WTP case. In Brazil, there is no specific legislation that considers taxes or fees for those who emit excess CO2. However, due to global trends related to climate change, it is important to consider the possibility that this reduction in emissions can translate into resources that enable this kind of projects.
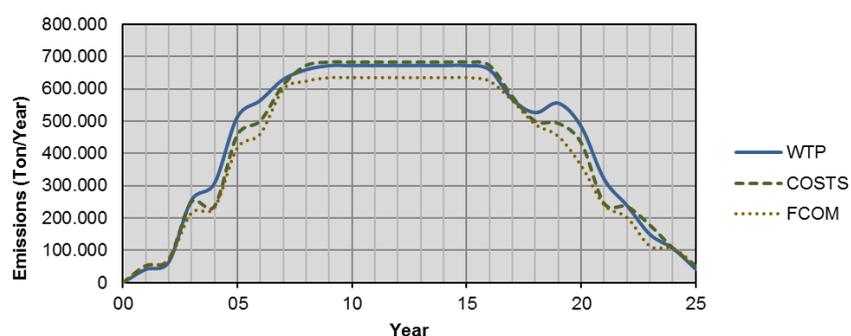

Figure 11 Comparison of CO_2 emissions

Table 4 Emissions compared to Base Case

Optimization Case				Business-As-Usual	
Emissions (Ton)	WTP	COSTS	FCOM	Emissions (Ton) Base Case	
Power Hub	571.642	683.234	635.320	-	
FPSOs	43.616	43.616	43.616	**Generator Sets**	350.120
Total	615.258	726.850	678.936	**Turbo-compressors**	72.186
Each FPSO	**316.43**	**353.62**	**337.65**	**FPSO**	**422.306**

4. CONCLUSIONS AND FINAL REMARKS

Optimized variables allowed creating an alternate energy supply scenario for three FPSOs. Three different objectives were established: cost minimization (COSTS), weight / power ratio (WTP) minimization, and fuel economy minimization over the operating time of the platforms (FPSO). The three cases vary between 200 and 300 MW of installed capacity, with equipment prices between 100 and 200 MMUSD. In all three cases, a significant reduction of CO_2 emissions was obtained, ranging from 16% to 25% with respect to the base project, highlighting the selection of the gas turbine as a factor with great influence on this result. The LM6000 turbine generates more energy per amount of CO_2 emitted than the LM2500. In contrast, the configuration that resulted in lower consumption over the life time, has the LM2500 turbine, although this provides less efficiency in generation. This result is explained by the partial loads, especially in the firsts and last years, where more distributed generation allows the entry of more steam turbines, which causes a decrease in fuel consumption. Very low partial loads of the combined cycles were avoided and therefore priority was given to the gradual operation of blocks, instead of operating them simultaneously. In order to establish a better economic outlook, it would be necessary to estimate the costs of the structure that would sustain such equipment at sea. It would also require an estimation of the electrical transformers and the setting of scenarios where it would be possible to send energy to the continent through submerged cables. Economic benefits could be obtained by selling energy or selling carbon credits, these scenarios would lead to important legislative considerations.

This initial study aimed to observe the behavior electric demand integration in FPSOs, in contrast to isolated supply. Results, in general, show theoretical significant decreases in fuel consumption and emissions produced. An important factor to improve overall performance integrating turbo-compressors electric demand, since it allowed to increase the scale economy of the combined cycle. The next studies to be carried out on Power Hubs should consider the aspects already mentioned, to obtain a better forecast of the economic and thermodynamic performance of this alternative.

5. ACKNOWLEDGEMENTS

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