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LIFETIME EXERGY ANALYSIS OF ELECTRICITY AND HOT WATER PRODUCTION SYSTEMS IN OFFSHORE PROJECTS WITH MULTIPLE PLATFORMS

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Abstract. *Systems for production of electricity and pressurized hot water in offshore oil and gas production platforms are typically designed with open cycle gas turbines with waste heat recovery units due to high power demands combined with area and weight constraints. This paper aims to present the results of an investigation on the exergy efficiency of two alternative designs to that adopted in Pre-Salt platforms. The first alternative considers the replacement of the GE LM2500+ gas turbines by GE LM2500PE combined-cycle units, thus maintaining the energy self-sufficiency of each platform. The second considers a central power plant with GE LM6000PG combined-cycle units to supply the electrical demand of four platforms and gas heaters for hot water in each production platform. This work also considers a delay of production between platforms of 1 to 4 years, changing the lifetime curves of electric and thermal demands of the multi-platform production system. In general, the Alternative 1 shows the highest exergy efficiency throughout the oil field life. However, this technical solution is quite challenging for future projects due to a severe Rankine cycle allocation restriction onboard. The centralization of the electricity production in high efficiency combined-cycle power plants did not show advantage over the traditional platform design with open-cycle gas turbines with exhaust gases energy recovery for hot water production. The production starting time changing from 1 to 4 years did not modify the conclusion of this work.*

Keywords: *offshore platform, power and heat systems, exergy analysis, project life*

1. INTRODUCTION

The U.S. Energy Information Administration (2016a) believes that global energy consumption may grow 48 % from 2012 to 2040. This forecast takes into account the perspective of economic growth that the developing countries showed in the last decades, in particular, China and India. The energy demand from the Organisation for Economic Co-operation and Development (OECD) countries may be increased by 18 %. Additionally, non-OECD countries may reach an increase of 71 % at the same period. By 2040, the energy demand from non-OECD countries could account for two-thirds of the world energy demand.

According to British Petroleum (2017), the world will face major changes in its energy matrix in the coming decades. The natural gas will gradually assume your importance to the society. Mineral coal for energy purposes will be less and less used as part of an effort of replacement by fuels with lower greenhouse gas emissions. The share of primary renewable sources, although still small, will grow 7.1 % per year in average up to 2035, when it will represent 10 % of the global energy matrix. Renewables may supply more energy than nuclear or hydroelectric by 2035. The Organization of the Petroleum Exporting Countries (2016) believes that natural gas will be the world's first primary energy source by 2040 accounting for 26.6 % of global energy demand.

Despite the fast-growth renewable market, fossil fuels still have a strategic role in meeting the world's energy demand in the coming decades. The offshore production will remain relevant in this scenario accounting for 29 % of world oil production in 2015, according to the U.S. Energy Information Administration (2016b). Saudi Arabia, Brazil, Mexico, the United States of America and Norway are the largest producers with 43 % of the offshore oil production. Offshore oil and natural gas production is even more strategic to Brazil. The National Agency of Petroleum, Natural Gas and Biofuels (2016) affirms that offshore oil and gas accounts for 93 % and 76 % of the overall Brazilian production in 2015, respectively.

Technological development will enable the society to use energy with more efficiency and less environmental impact. According to ExxonMobil (2017), the society's commitment to the rational use of energy could reduce 2.0 % per year average in the energy intensity index from 2015 to 2040. Moreover, the carbon intensity index - carbon dioxide emissions per unit of energy used - can be reduced significantly by 2040. The U.S. Energy Information Administration (2016a) estimates that global carbon dioxide emissions could increase by 32 % from 2012 to 2040 even with the current efforts of the society to promote rational energy use. This is explained by the fast-growth expected in emerging economies. OECD nations will also face an increase in carbon dioxide emissions although much smaller than those from the non-OECD countries.

1.1 General characteristics of oil and gas platforms

According to Nguyen (2014), the basic function of an offshore production platform is to receive the fluids produced in a given field separating oil, gas and water. The oil is then processed to meet the market specifications. The associated gas receives a treatment before being exported, reinjected back into the reservoir or used for artificial lifting. The water also undergoes a treatment before being discarded at sea or reinjected according to the local specifications.

The design of the primary processing plant of an offshore production platform is premised on the characteristics of the field where it will operate, such as, temperature, pressure and composition of the produced hydrocarbons, gas-oil and water-oil ratios, final specification of the produced oil and associated gas and operational strategies. These parameters are subject to huge variations throughout the oil field life. The most common changings are the reduction of the well pressure with progressive increase in water production.

Therefore, significant variations in power and heat demands of the processing plant are expected throughout the platform lifetime. Gallo et al. (2017) provided curves of electric and thermal demands of a Pre-Salt platform, as shown at Figure 1. In Mode A, the pressure of the produced gas is increased by compressors driven by electric motors. In Mode B, compressed gas is separated into two streams, one rich in hydrocarbon and the other rich in carbon dioxide. The stream rich in hydrocarbon goes to compressors driven by electric motors, while the carbon dioxide rich stream goes to compressors driven by gas turbines, called CO_2 Turbines.

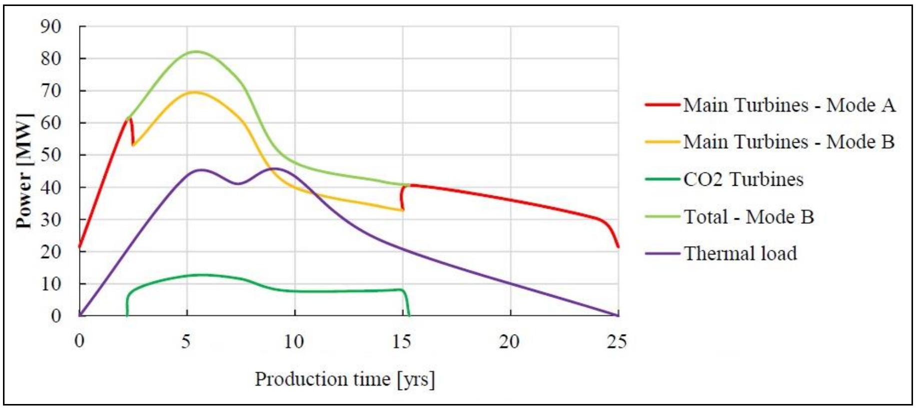

Figure 1. Power and heat demand of a Pre-Salt platform (Gallo et al., 2017)

1.2 Electricity and hot water production in offshore platforms

According to Nguyen et al. (2016), offshore production platforms accounted for 26 % of the overall carbon dioxide emissions in Norway in 2011. In 2017, about 85% of the overall carbon dioxide emission related to the petroleum activity in Norway is related to the turbines (Norskpetroleum, 2018). Petroleum companies with operations in Norway have to pay a carbon dioxide emission tax, which amounts to about US$ 67.00 per tonne of carbon dioxide currently.

Power and heat demands undergo profound changes throughout the project life. This causes the electrical and hot water production system to operate most of the time in partial-load, frequently, as low as 60 to 70 % nominal. The rotating machinery operates far away from its best efficiency point penalizing the exergy efficiency and carbon dioxide emissions. For example, the platform from Gallo et al. (2017) has an installed capacity of 100 MW electrical and through Figure 1 one can note that the demand use to be as low as 50 MW.

De Oliveira Jr. and Van Hombeeck (1997) published the first work on exergy analysis of production platforms. The authors propose the recovery of the residual heat from gas turbines exhaust gases to enhance the produced fluids temperature before the primary processing plant. This design solution increased the overall exergy efficiency of the platform. The proposed configuration is currently the standard design of offshore primary processing plants.

Kloster (1999) argues that the increasing commercial value of natural gas and the taxation of greenhouse gas emissions in Norway motivated operational and technological development initiatives for the rational use of energy in offshore installations. The adoption of combined-cycle systems is indicated as a viable alternative to achieve energy efficiencies about 50 % and 80 % with cogeneration. This configuration can result in consumption and emission reductions of 25% compared to open-cycle systems.

Pierobon et al. (2013) optimized an organic Rankine cycle to enhance the power production in a platform. The heat is supplied by exhaust gases of gas turbines. The authors recommend acetone and cyclopentane as the best working fluids for this application. The association of an organic Rankine cycle with acetone to a Siemens SGT-500 gas turbine increased the thermal efficiency in 23.7 to 27 % with an added volume of 14.5 to 57.5 m^3 and return in terms of net present value of US$ 17.7 million to US$ 19.8 million.

Barrera, Bazzo and Kami (2015) proposed an organic Rankine cycle for the recovery of residual heat from gas turbines exhaust gases. The integration of the organic Rankine cycle resulted in a reduction in energy consumption per barrel of produced oil from 15 to 20 % with an increase in the exergy efficiency indicator of the platform of 14 to 20 %. The largest portion of the exergy destruction is placed in gas turbines followed by the separation plant and injection systems for gas and water.

Nord, Martelli and Bolland (2014) optimized the power and weight of a steam Rankine cycle of a production platform. Univariate optimization was used with the objective of maximize the power-to-weight ratio of the plant. A multivariate optimization was then performed to maximize the power output without compromising the target weight. In this work, the weight-to-power ratio was reduced by 4 % compared to the reference design.

Greenhouse gases emissions reduction can be achieved with carbon capture and storage systems (CCS). Carranza-Sánchez and de Oliveira Jr. (2015a) evaluated the influence of the CCS on the exergy efficiency of a Pre-Salt platform. The system is based on the chemical absorption technology per monoethanolamine solution (MEA). In this case, the introduction of the CCS reduced in 77 % the carbon dioxide emissions into the atmosphere, but reduced the platform exergy efficiency in 2.8 %.

Da Silva and de Oliveira Jr. (2018) assessed the exergy cost of oil and gas along the lifespan of a platform. The work takes into account the off-design operation of the process and cogeneration plants. The exergy cost of oil varies from 1.0 kJ/kJ to 3.2 kJ/kJ along the well lifespan depending on process plant operating mode and cogeneration plant configuration. Similarly, the exergy cost of gas varies from 1.0 kJ/kJ to 2.4 kJ/kJ. The average emission of carbon dioxide for the natural gas ranges from 19.0 gCO_2/MJ to 19.8 gCO_2/MJ depending on the cogeneration plant configuration. For oil it ranges from 19.4 gCO_2/MJ to 26.8 gCO_2/MJ depending on the process plant operating mode.

2. EXERGY AND EXERGY EFFICIENCY

Exergy is defined as the maximum available work that can be obtained from a thermodynamic system through its interaction with the environment through processes that are reversible up to steady state. This paper considers the environmental components defined by Szargut, Morris and Steward (1988). Neglecting nuclear, magnetic, electric, and surface tension effects, the specific exergy (b) can be divided in four specific exergy components: potential (b_{pot}), kinetic (b_{kin}), thermomechanical or physical (b_{ph}) and chemical (b_{ch}), according to Eq. (1).

$$b = b_{pot} + b_{kin} + b_{ph} + b_{ch} \tag{1}$$

As kinetic and potential energy can be completely converted into work, the kinetic and potential specific exergy can be calculated by Eq. (2) and (3), respectively, from the gravity (g), height (z) and speed (v).

$$b_{pot} = gz \tag{2}$$

$$b_{kin} = \frac{1}{2}v^2 \tag{3}$$

For a perfect gas with constant specific heat at constant pressure the specific physical exergy can be calculated based on the pressure (p) and temperature (T), pressure (p_0) and temperature (T_0) at dead state, gas constant (R) and specific heat at constant pressure (c_p), according to Eq. (4):

$$b_{ph} = c_p\left[\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right] + RT_0 \ln\left(\frac{p}{p_0}\right) \tag{4}$$

The specific molar chemical exergy of mixtures can be calculated by Eq. (5), where x_i is the molar fraction of the substance, γ_i the activity coefficient of the substance in the mixture and $\bar{b}_{ch,i}$ the specific standard molar chemical exergy of the component i:

$$\bar{b}_{ch} = \sum_i x_i \bar{b}_{ch,i} + RT_0 \sum_i x_i \ln \gamma_i x_i \tag{5}$$

Equation (5) is useful especially when calculating the specific chemical exergy of gaseous fuels with determined chemical composition. However, solid and liquid industrial fuels are often mixtures of numerous chemical compounds of a generally unknown nature. In this case, Kotas (1995) proposes the calculation of the specific chemical exergy of the fuel as a function of its lower heating value (LHV) and the factor (ϕ) by Eq. (6). Factor ϕ is about 1.04 for natural gas.

$$b_{ch} = \phi LHV \tag{6}$$

There are many expressions in the literature to calculate the exergy efficiency of energy conversion processes. One commonly adopted in thermal processes is shown below. This work considers the driving exergy supplied by the gas produced in the platform. Kinetic, potential and physical exergy of the fuel has been neglected due to its irrelevance in this calculation. The useful exergy effect is the production of a certain amount of electricity (pure exergy by definition) and increasing of the temperature of a hot water flow to warm up the produced fluids. Therefore, the exergy efficiency of the electricity and hot water production systems is determined by Eq. (7):

$$\eta_{ex} = \frac{\text{Useful exergy effect}}{\text{Driving exergy}} = \frac{\dot{B}_{el} + \dot{m}_w \left(b_{out} - b_{in}\right)}{\dot{m}_f b_{ch}} \tag{7}$$

3. ASSESSMENT OF OIL FIELD PRODUCTION DEVELOPMENT PROJECTS

According to Nunes et al. (2016), offshore production development projects in Brazil with multiple identical platforms started with Petrobras 58 and 62. The authors presented a detailed analysis of the standardization process pointing out the reduction of the schedule and costs as the motivation towards a single topside design for different oil fields. Such design philosophy tends to be more attractive compared to the apparent advantage of optimized designs. According to the authors, the most recent project at that time regards eight platforms, project named Replicantes.

With the location of multiple platforms in a certain region offshore it is reasonable to think in a central power generation system. This power hub may be an attractive solution to overcome weight and area constraints, thus, enabling more efficient combined-cycle power plants and also post-combustion CCS technologies to mitigate the emissions of greenhouse gases. On the other hand, platforms without power generation system lose their inherent ability to produce hot water by saving gas turbines exhaust gases useful exergy. Therefore, supplementary hot water supply by high-efficiency gas heaters is required in the alternative design options.

In multi-platform projects, there is usually a time interval in the production startup of the unit. For this reason, this work evaluates the influence of this interval on the global electric and thermal demand curves of the multi-platform system and, consequently, the exergy efficiency throughout the project life. Three configurations for electricity and hot water production systems are compared, as detailed below.

Lifetime electric and thermal demand curves are not function of the topside design solely. Chemical composition, physical-chemical properties and water-oil-gas ratio of the produced fluids change significantly with time and exert a great influence on the fluids warm-up process and fluid handling machinery driving loads. All those factors use to be very hard to be predicted with reasonable accuracy. For this reason, this work considers a very first approach by adopting the same power and heat lifetime demand for all units.

Demand curves for this work are derived from the work of Gallo et al. (2017), as shown at Figure 1. The only changing regards the use of electric motors to drive the compressors of the CO_2 Turbines. The electric and thermal demand curves adopted in this paper are shown at Figure 2 below.

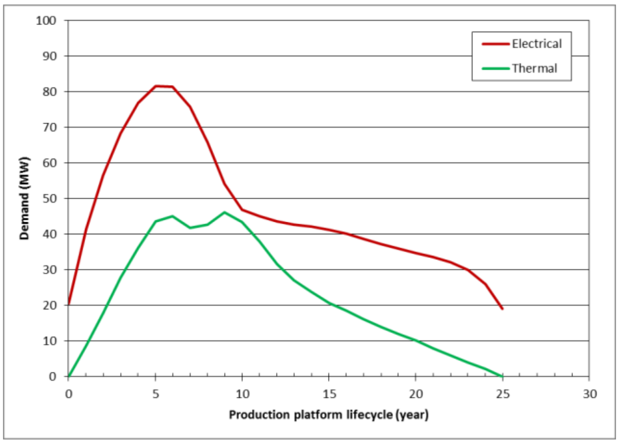

Figure 2. Production platform electric and thermal demands

The Base Case considers the actual design of the electric and thermal systems of the Pre-Salt platforms. This technical solution is compared with two alternative design options, hereinafter called Alternative 1 and 2. The first considers the replacement of open-cycle gas turbines with waste heat recovery units by combined-cycle units composed of smaller gas turbines and steam turbines in order to reach the same nominal power and hot water production by heat recovery steam generators and supplementary gas heaters. The second considers a central power hub to produce electricity for all platforms. In this case, each platform has its own gas heaters to meet the thermal demand. A basic description is provided below followed by the technical specification at Table 1:

- Base Case: Each production platform with four General Electric LM2500+ gas turbines with waste heat recovery units;
- Alternative 1: Each production platform with four General Electric LM2500PE gas turbines with heat recovery steam generators and single pressure level condensing steam turbines. Supplementary gas heaters for hot water production;
- Alternative 2: Central power hub with six General Electric LM6000PG gas turbines with heat recovery steam generators and single pressure level condensing steam turbines. Main gas heaters in all platforms for hot water production.

Table 1. Power and heat system technical characteristics at ISO condition

		Base Case	Alternative 1	Alternative 2
Nominal power (MW)	Gas turbine	30.226	23.292	53.980
	Steam turbine	-	9.444	17.330
Nominal efficiency (%)		39.6	50.4	52.3
Nominal air flow (kg/s)		84.3	69.4	143.3
Cogeneration capability?		Yes	Yes	No
Gas heaters needed?		No	Yes	Yes
Gas heaters thermal efficiency (%)		-	94	94

The associated gas produced in the oil fields is treated and supplied to turbines and heaters as specified at Table 2. Design and off-design thermodynamic cycles were simulated by using gas turbines black-box models from GateCycle® version 6.1.2. Simulations were carried out considering the annual average environmental condition at Pre-Salt region: ambient temperature of 25 °C, barometric pressure of 101.325 kPa and 76 % relative humidity. For the exergy analysis, this work uses the reference environment and standard chemical exergy proposed by Szargut, Morris and Steward (1988). For information, the fuel chemical composition shown in Table 2 has a molecular weight of 18.33 and lower heating value of 47.45 MJ/kg.

Table 2. Associated gas specification and standard chemical exergy

Substance	Molar fraction (%)	Molar mass	Standard molar chemical exergy (kJ/mol)
Methane	75.68	16.04	832
Ethane	10.96	30.07	1496
Propane	6.62	44.10	2154
Isobutane	0.92	58.12	2806
N-butane	1.55	58.12	2806
Pentane	0.31	72.15	3463
Hexane	0.83	86.18	4119
Heptane	0.20	100.21	4762
Nitrogen	0.56	28.15	1
Carbon dioxide	3.00	44.01	20

4. RESULTS

Based on the electric and thermal demand curves of the platforms, available in Figure 2, it was determined the demand curves of the production development project with four platforms considering intervals of one to four years among platforms' start-up. It is possible to notice a nominal power decay of the multi-platform project when the start-up interval increases. This can be explained by the mismatch among peaks of demands, which occurs in longer projects. This feature is particularly interesting for capital cost optimization, as the capital invested in electric and thermal systems is a direct function of the power plant nominal power. However, the optimization of capital costs is not the focus of this work.

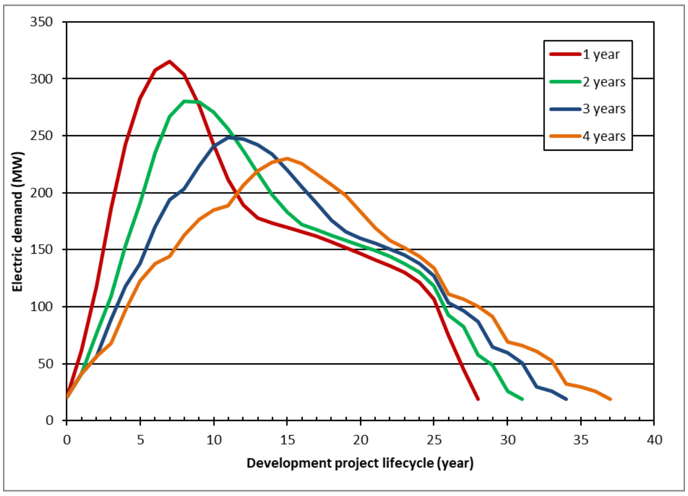

Figure 3. Lifetime electric demand of a development project with four platforms considering different starting intervals

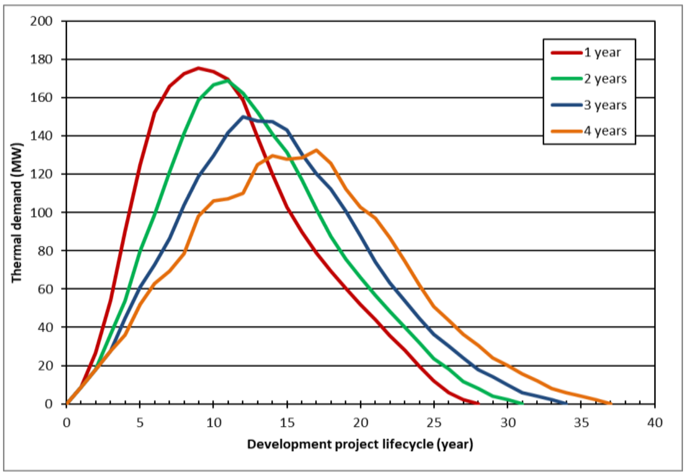

Figure 4. Lifetime thermal demand of a development project with four platforms considering different starting intervals

It should be emphasized that offshore gas turbines typically operate away from their rated capacity in order to avoid unexpected outages due to sudden changes in operating parameters and reaching the limits of the protection system. For this reason, this work considers a target operating range of 60 to 80% of their nominal power throughout the entire project life. To operate at this range is compatible with the current practice in the oil and gas industry. Therefore, the thermal efficiency (energy) curves considering 30 to 100% capacity of the power generation system were obtained for all three cases being investigated, according to Figure 5.

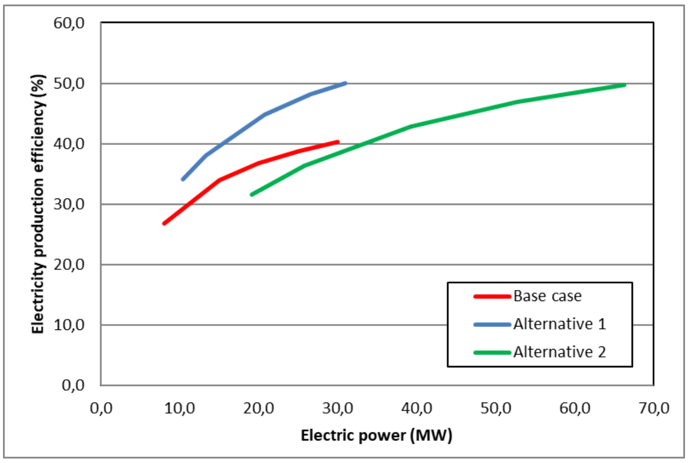

Figure 5. Thermal efficiencies of the power plants at the average Pre-salt ambient condition

Hot water production capacity at heat recovery units was evaluated. The production capacity from exhaust gases for Base Case and Alternative 1 according to the electric power production is shown at Figure 6. The operational limit of hot water production considers 15 °C margin on the exhaust gases temperature at stack to avoid wet corrosion. The curve for Base Case considers the power being produced by one gas turbine only, whereas Alternative 1 the power produced by one gas turbine plus one steam turbine. The pressurized hot water reaches the heat recovery units at 100 °C and 1,040 kPa, where its temperature is raised to 130 °C and the pressure reduced to 990 kPa.

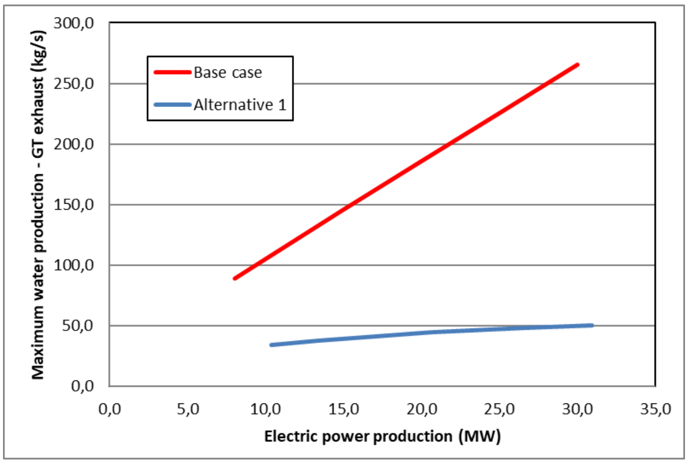

Figure 6. Maximum hot water production by gas turbine exhaust gases at the average Pre-salt ambient condition

According to Figure 7, Base Case is self-sufficient in terms of hot water production throughout the platform operating life. There is more than 23% surplus capacity and the most stringent moment occurs after 10 years of the production starting. At year 10, the thermal demand is reasonably close to the historical maximum, but the electric demand is far below the maximum one. Therefore, the calculated margin shown at Figure 6 is an indirect measure of the exergy destruction that occurs at Base Case, once the exhaust gases are released to the environment at temperatures well above the minimum allowable at the stack.

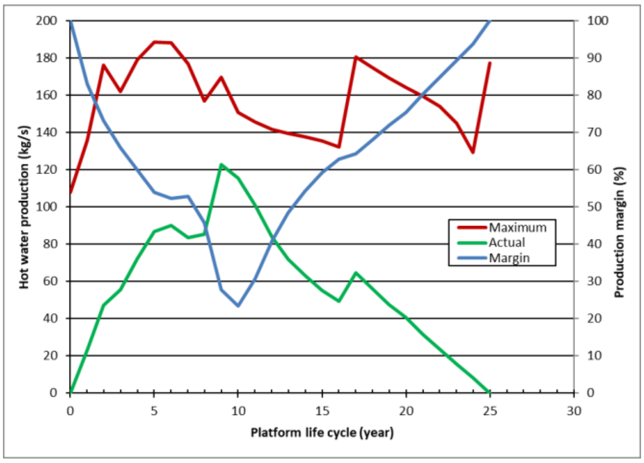

Figure 7. Lifetime hot water production by the exhaust gases at Base Case

Supplementary gas heaters were added at Alternative 1 to fulfill the gap of hot water production from year 2 to 19. At Figure 8, it is possible to note a negative margin at this time range, which means that the hot water demand overcomes the capacity of the combined-cycle power plant. This characteristic is caused by the majority of heat being used by the Rankine cycle. Although the useful physical exergy of exhaust gases is transferred to the products, the supplementary production of hot water causes a considerable destruction of the fuel gas exergy. In Alternative 2, by definition, the hot water is produced only in production platforms onboard gas heaters.

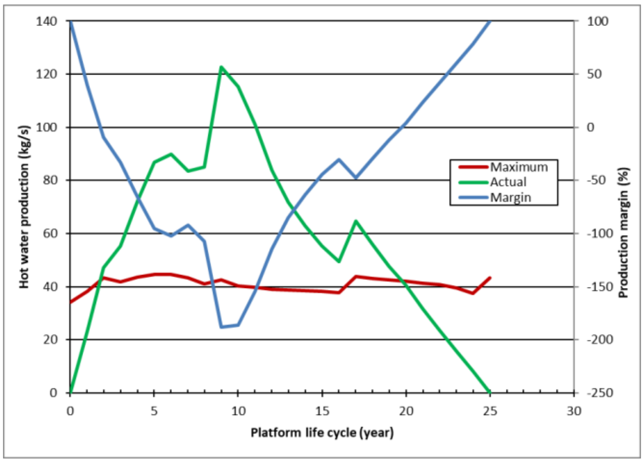

Figure 8. Lifetime hot water production by the exhaust gases at Alternative 1

The exergy efficiency of the production development project was then obtained based on the above methodology and assumptions. The lifetime exergy efficiency for all cases and production start-up interval is shown at Figure 9. In general, Alternative 1 presented the best results with average efficiencies ranging from 42.04 to 42.40% from 1 to 4 years' start-up interval, respectively. A prominent decay of almost 5% in exergy efficiency is observed at Alternative 1 close to year 15 with start-up intervals of 1 and 2 years due to greater loads in the supplementary gas heaters.

Alternative 2 maximizes the exhaust gases exergy savings for power generation, but still requires a considerable amount of fuel gas to meet the thermal demand. The apparent advantage of the combined-cycle power plant opposes to the low exergy efficiency of the gas heaters. Alternative 2 does not show exergy efficiency advantage compared to the Base Case. The lifetime exergy efficiency of Alternative 2 reduces from 38.65 to 38.06 % from 1 to 4 years' start-up interval, whereas Base Case increases from 37.74 to 37.93%, respectively. Through the graphics, one can note that Base Case tends to have higher exergy efficiency than Alternative 2 when thermal demand is close to the maximum, i.e., when the exergy destruction in gas heaters are also close to the maximum.

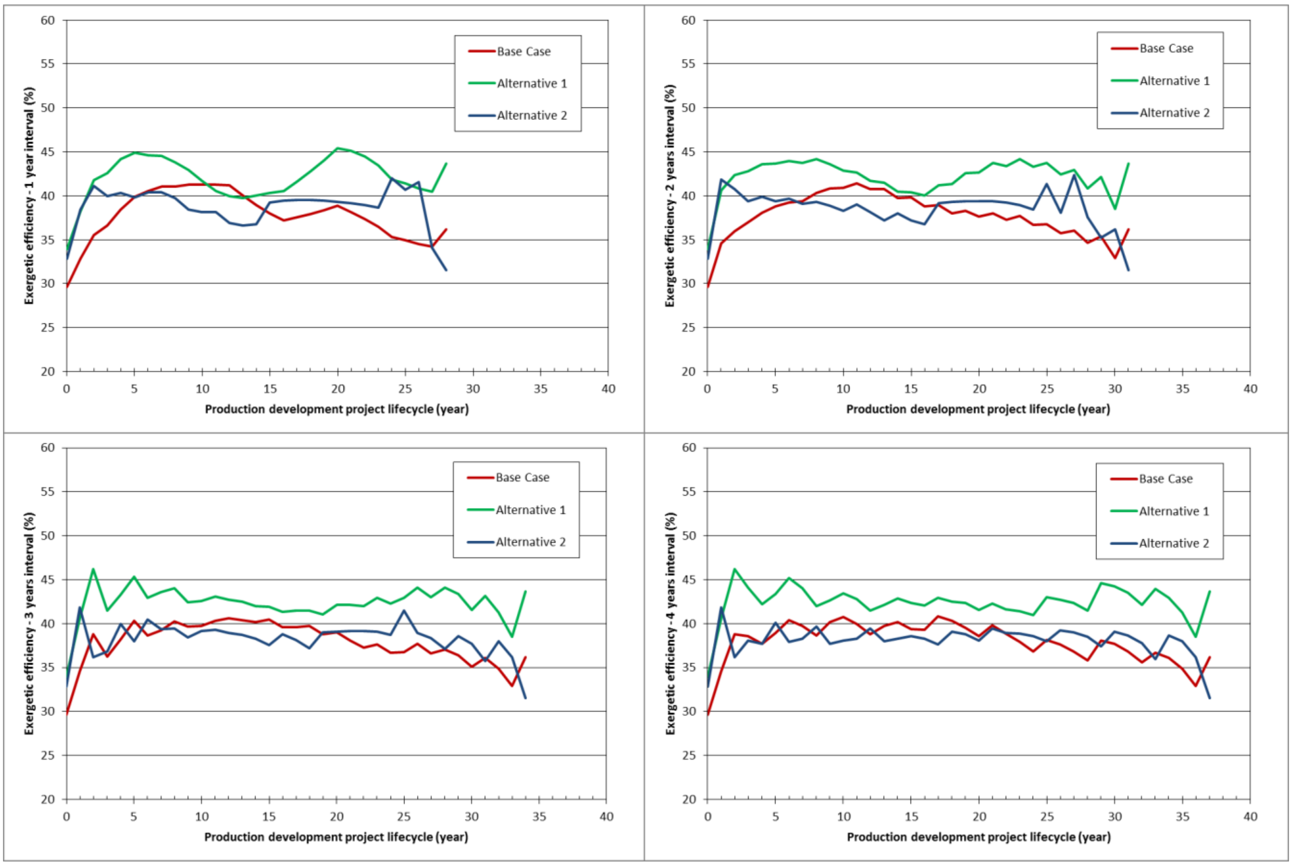

Figure 7. Production development projects lifetime exergy efficiencies

5. CONCLUSION

The lifetime exergy analysis of the electricity and hot water production systems in an offshore production development project with four identical platforms was carried out successfully. Through the developed case study, it is noticed that Alternative 1 presents the highest lifetime exergy efficiency for the multi-platform production development project investigated, regardless the platforms production startup interval.

The average exergy efficiency of Alternative 1 resulted 11.4, 11.1, 10.6 and 9.9% higher than the Base Case, considering the platforms production startup intervals of 1 to 4 years, respectively. Similarly, Alternative 2 resulted in 2.4, 2.4, 0.7 and -0.3% compared to the Base Case, respectively. In Alternative 1 and 2, electricity production is carried out in combined cycle plants, which are more efficient than the single cycle plant in the Base Case. While the Base Case destroys a significant portion of the available exergy in the exhaust gases, Alternative 1 and 2 also have their overall efficiency affected by the burning of combustible gas in gas heaters for the production of water at 130 ° C, even using devices with 94% energy efficiency.

This research paves the way for future analyzes aimed at optimizing the production systems for electricity and hot water in this and other offshore production development scenarios. In this context, the authors acknowledge the need for future work investigating new plant configurations, as well as the optimization of design parameters and production costs analysis.

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7. RESPONSIBILITY NOTICE

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