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EXERGOECONOMIC ANALYSIS OF A COGENERATION PLANT ON A BRAZILIAN PRE-SALT FPSO CONSIDERING DIFFERENT FUEL GAS COMPOSITIONS

Rodrigo Dias

Waldyr Luiz Ribeiro Gallo

rdias@fem.unicamp.br

gallo@fem.unicamp.br

State University of Campinas

Rua Mendeleyev, 200, 13083-860, Campinas, Sao Paulo, Brazil

Abstract. *Natural gas has often been used as a power supply in oil platforms due to its abundance and flexibility. Nowadays, major concerns over enviromental issues, and consequently, efficiency of energy conversion have taken the analysis to the next level, which relates strongly with the rational consumption of fossil fuels, such as natural gas, because of the low efficiencies yet experienced. The goal of this work is to provide a complete analysis of a cogeneration plant at a Brazilian pre-salt oil offshore platform composed of four gas turbines for power generation (100 MW installed) and heat exchangers fed by the exhaust gases, transferring recovered energy to process water; this picture of the plant shows an efficiency of only around 55%, which is very low for cogeneration. To accomplish that, an exergetic and thermoeconomic analysis will be essential in order to point out where the most part of irreversibilities are generated and the most costly flows are located, in energetic or monetary terms, despite of presenting the allocation of* CO_2 *emissions between heat and power. The analysis will be extended to two cases of fuel composition, according to the local characteristics of the field and the period of production.*

Keywords: *Exergy, Thermoeconomics, Natural Gas, Oil, Cogeneration*

1 INTRODUCTION

The oil & gas industry represents a great share of the world's energy matrix. While renewable resources take an increasingly important role in this context, oil and natural gas are still indispensable. According to the IEA (*International Energy Administration*), 52.4 % of the world energy production and 52.7 % of the total primary energy supply were based on O&G products, in 2012.

It is usually regarded to the final usage of petroleum fuels as a threat to the climate change issues; however, the exploration and production must be taken into consideration as well, as an inefficient design at this stage may compromise significantly the whole life cycle. Alongside environmental concerns and efficiency improvement are the economic costs, which are very important in almost every industry.

A FPSO (*Floating Production Storage and Offloading*), which is a type of offshore platform, located at the Brazilian pre-salt fields, is designed to explore them and produce, at first, oil for exportation; furthermore, natural gas has a key role in this process, as it has multiple usages: oil gas lift, field injection, exportation (pipelines or liquefied), consumption or flaring/venting. The objective is, certainly, to use the resource in the most rational way, which means designing an efficient electrical generation facility for its own consumption and letting the least possible portion go to the atmosphere. The electrical generation facility is a cogeneration plant, which supplies the system with both electricity, from gas turbines, and heat, from the exhaust gases' high temperature.

The main goal of this work is to analyze from different perspectives the current status of a real cogeneration plant located at the pre-salt fields, including exergetic, thermoeconomic and environmental assessments. The plant has a total 100 MW of power capacity, divided into 4 gas turbines (25 MW each), but one of them is kept turned off, except for emergency or maintenance procedures. The critical heat demand is of 53.5 MW, divided equally into the three active turbines, and it will not vary for the simulated cases.

The analysis is extended considering different load conditions for the gas turbines because of the electrical and thermal demand variations along with time, mode of operation and field composition. Also, two very distinct fuels that may be available considering different situations: one rich in methane and one rich in CO_2 (which is common at the pre-salt), are simulated in order to determine the plant's parameters reaction to those changes.

The exergetic analysis is essential for detecting the main spots where irreversibilities occur, as well as determining the cogeneration losses and allocating those to the products (heat and power). Additionally, the thermoeconomic analysis seeks to determine the costs of the products based on the fuel and equipment's price. To give a complete outlook of the plant, an environmental analysis brings up the total CO_2 emissions.

Many works such as de Oliveira Jr, Sanchez (2014), Van Nguyen (2014), Voldsund (2014) and Voldsund et al. (2012) have dealt with the exergetic analysis of the O&G process and utility plants, but they were not focused on the gas turbines as much as it will be presented; the main reason for this point of view is the massive importance of this plant in terms of irreversibilities for the whole system.

2 METHODOLOGY

The cogeneration plant, consisting of a gas turbine and a heat exchanger at the bottom, is represented below. It is important to say that in the actual plant there are three of these working equally. The material flows are numbered and their composition type is shown at the legend.

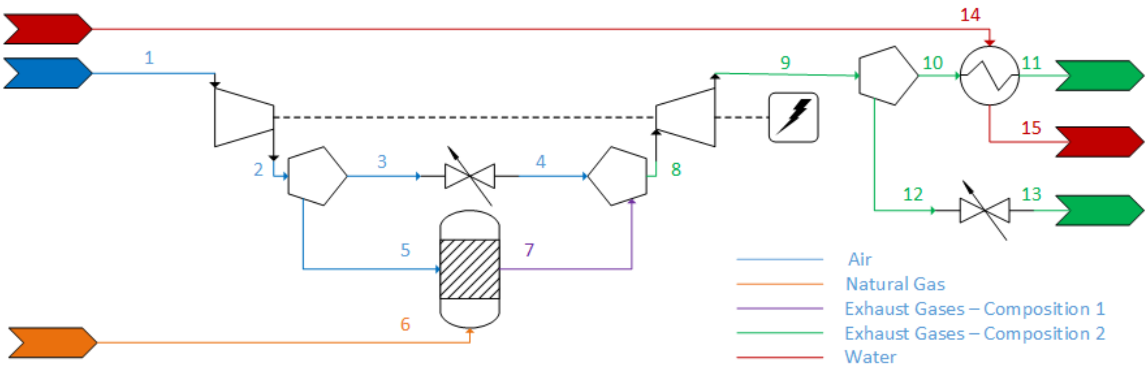


Figure 1: Cogeneration plant

As it can be seen, the gas turbine is composed of a gas compressor linked to the gas expander and an electric generator through a shaft system. After gas compression, the air goes to the combustion chamber for fuel burning, and is partially by-passed for cooling the expander impellers; the combustion products are then expanded, completing the electric system. The exhaust gases leaving the gas turbine at a sufficiently higher pressure than atmosphere to compensate the pressure losses at the heat exchanger raises the temperature of process water, and partially by-passes the heat exchanger as the process water temperature is determined and the heat exchanger has a fixed geometry.

In order to simulate this system just described before, powerful computational resources are required, as a huge series of data including : flow composition, thermodynamic properties and equipments' performance, are calculated. Two softwares were very well-suited for that end: Thermoflex®, by Thermoflow and EES®(*Engineering Equation Solver*), by F-Chart; both are licensed at the Faculty of Mechanical Engineering.

The software Thermoflex®also has valuable information over the gas turbine working conditions, including internal physical properties, compositions and its electric generator efficiency. The model used on this work is the Rolls-Royce RB 211 gas turbine; its nominal conditions are presented on Table 1, with respect to the ISO conditions. Nevertheless, the real conditions are not equal to the nominal, as the reference temperature is 25 ^{o}C.

It is prudent to divide the methodology into two main branches: the thermodynamic, including the exergetic parameters, and the thermoeconomic; this sort of arrangement seeks to bring more clearance to the ideas and hypothesis developed.

The heat transfer phenomenon occurs in a specific heat exchanger model, which is brought to its operation mode depending on the exhaust gases' transport properties. As it is not the main objective of this work, this part of the simulation will not be extended, but it is important to mention that the electrical part-load condition brings different heat transfer conditions.

Table 1: Rolls Royce RB 211 - Nominal working conditions

Parameters	Nominal value
Pressure ratio	20.8
Turbine inlet temperature [^{o}C]	1227
Turbine exhaust temperature [^{o}C]	492
Air flow [kg/s]	90
Generated power [kW]	27240
1^{st} Law efficiency [%]	35.6
Price [10^6 US$] (2015 data)	11.2

2.1 Thermodynamic approach

Firstly, the thermodynamic approach will enable the system to be energetically described. By means of the 1^{st} Law of Thermodynamics, which conserves energy, it is possible to obtain the heat rejected in every device; however, it is through the 2^{nd} Law of Thermodynamics, that the entropy generation, related to the irreversibilities, are linked to each of the processes simulated, allowing a more realistic and rational view of the operating conditions. Also, from the exhaust gases' composition, the net CO_2 emissions are obtained.

For that end, the thermodynamic properties' reliability is essential, so the gases are brought to a common reference, taking into consideration their enthalpy of formation, in order to ease the writing of the program that will show the outputs investigated.

A mixture of gases has its own particular property equations, and they are not simple weighted averages of its constituents because of the gases' interaction. In this case, the gases are treated as ideal gases, which means that they obey the $pv = RT$ general law. Also, from that hypothesis, the enthalpy of the mixture is only dependent on its temperature, while the entropy is dependent on both temperature and pressure.

The enthalpy is, then, as it described in Klein, Nellis (2012), a simples weighted average of the gas fractions, but entropy is not, as it depends on pressure too. Each gas constituent of the mixture shares a partial pressure, which is proportional to its molar fraction because of the ideal gas model. The gas mixture enthalpy and entropy equations are presented below.

$$h_{mix} = \sum y_i h_i \tag{1}$$

$$s_{mix} = \sum y_i s_i - R \sum y_i ln(y_i) \tag{2}$$

Another fundamental part of the property work is to determine the physical and chemical exergies of the flows. The physical exergy is simply determined by the enthalpy and entropy of the mixture, as Bejan, Tsatsaronis, Moran (1996) suggests; the gas mixture chemical exergy has a close relation to the entropy formula, according to the same authors, for a very similar reason that will not be extended here. The chemical exergy values, for the gases in the reference state, were taken from Szargut, Morris, Steward (1988). The gas mixture physical and chemical exergies are presented below.

$$b_{ph,mix} = (h_{mix} - h_{0,mix}) - T_o(s_{mix} - s_{0,mix}) \quad (3)$$

$$b_{ch,mix} = \sum y_i b_{ch,i} + RT_o \sum y_i ln(y_i) \quad (4)$$

When it comes to the equipments of a cogeneration plant, certain performance parameters must be determined in order to assess their efficiency. Table 2 shows parameters of that kind chosen to be used in this work, based on the 2^{nd} Law of Thermodynamics.

Table 2: Exergetic performance parameters

Equipment	Efficiency formula
Compressor	$\frac{\dot{B}_{outlet}-\dot{B}_{inlet}}{\dot{W}_{shaft,compressor}}$
Combustion Chamber	$\frac{\dot{B}_{outlet}}{\dot{B}_{fuel}+\dot{B}_{air}}$
Turbine	$\frac{\dot{W}_{shaft,turbine}}{\dot{B}_{inlet}-\dot{B}_{outlet}}$
Recovery Heat Exchanger	$\frac{\left(\dot{B}_{outlet}-\dot{B}_{inlet}\right)_{water}}{\left(\dot{B}_{inlet}-\dot{B}_{outlet}\right)_{gases}}$
Generator	$\frac{\dot{W}_{gross}}{\dot{W}_{shaft}}$

Due to the many types of power flows present in the plant, they were organized in a particular way in order to give more clearance to the results. These types include: shaft, gross, net and auxiliary powers. Table 3 shows the type of power correspondent to its flow number. It is worth noting that the power flow numbers are immediately after the material flows present in Figure 1.

The total shaft power is the simple difference between the shaft power of the turbine and compressor; the gross power is the one obtained from the total shaft power, after passing the electrical generator; the auxiliary powers are an estimation of the required power for the machine operation, and the net power is the gross power minus the auxiliary powers.

Table 3: Power flows

Type	Flow number
Compressor shaft power	16
Turbine shaft power	17
Total shaft power	18
Gross power	19
Auxiliary power: compressor	20
Auxiliary power: turbine	21
Net power	22

Simulating the system considering two very distinct fuel compositions is very important, specially in the case of the offshore platform, that is normally fed by its own gas production, and presents great composition variation along with time. For observing the exergetic and thermoeconomic response of the system to these sort of variations, two fuel gases presented ahead on Table 4 are chosen.

Table 4: Fuel gas main characteristics

Properties	Fuel 1	Fuel 2
Nitrogen mol. frac. [%]	0.56	0.26
Carbon Dioxide mol. frac. [%]	3.00	60.16
Methane mol. frac [%]	75.68	32.22
Ethane mol. frac. [%]	10.96	3.63
Propane mol. frac. [%]	6.62	2.05
i-Butane mol. frac. [%]	0.92	0.29
n-Butane mol. frac. [%]	1.55	0.64
Pentane mol. frac. [%]	0.31	0.44
Hexane mol. frac. [%]	0.83	0.12
Heptane mol. frac. [%]	0.20	0.18
Lower heating value [kJ/kg]	45381	11492
Chemical exergy [kJ/kg]	47195	12367
$\frac{b_{ch}}{LHV}$	1.040	1.076

2.2 Thermoeconomic approach

Thermoeconomics is a broad field that has already immensely contributed to engineering and acts as an important complementary part of the exergetic analysis.

One of the first related work was brought up by Tribus, Evans, Creelin (1966), dealing with the costs of water desalination. Thereafter, in the 1980's, specially, an extense series of methodologies in the field has been developed. In the 1990's, a group of thermoeconomics researchers have united to show the application of their own methodology into one simple and coincident problem, to what became known as the CGAM problem which is present in Valero et al. (1993) and consists of a cogeneration plant containing an air pre-heater (regenerator), located before the combustion chamber, that recovers heat from the exhaust gases.

More important to this work are the Theory of the Exergetic Cost, developed by Valero, Lozano (1993), and the field of Exergoeconomics, developed by Tsatsaronis, Pisa (1993). These are based on rational propositions, showing the cost of production of every flow, in exergetic and monetary terms, being, therefore, really important in the present context because of the fact that process water and electricity shall be allocated in terms of the costs of production. There are 22 flows (material and electrical), so 22 equations should be determined in order to solve the linear system. Such equations depend on the exergy of the flows (exergetic analysis) and on the fuel and equipment's costs (exergoeconomic analysis).

The thermoeconomic balance, relative to the two methodologies described previously are presented ahead in the order of citation.

$$\sum \dot{B}^*_{inlet} = \sum \dot{B}^*_{outlet} \tag{5}$$

$$\sum \dot{C}_{inlet} + \dot{Z}_{IC} + \dot{Z}_{OM} = \sum \dot{C}_{outlet} \tag{6}$$

The fuel specific cost (for fuel 1) was based on the work of Tsatsaronis, Pisa (1993), corresponding to US$ 4/GJ. Also, an important hypothesis adopted states that the fuel cost for both fuels' systems is the same, suggesting that the lower quality of fuel 2 compensates the higher mass flow needed in this case, resulting on the same cost. This particular topic is a field of many possible variations, though.

It must be pointed out that the investment costs and the operation & management costs can be condensed into one term ($\dot{Z}$), according to the following equation present on Tsatsaronis, Pisa (1993), where $\phi = 1 + \frac{Z_{OM}}{Z_{IC}}$, CRF is the Capital Recovery Factor, in percentage terms, and N is the yearly operation time, in hours.

$$\dot{Z} = Z \ \ \frac{\phi \ \ CRF}{3600N} \tag{7}$$

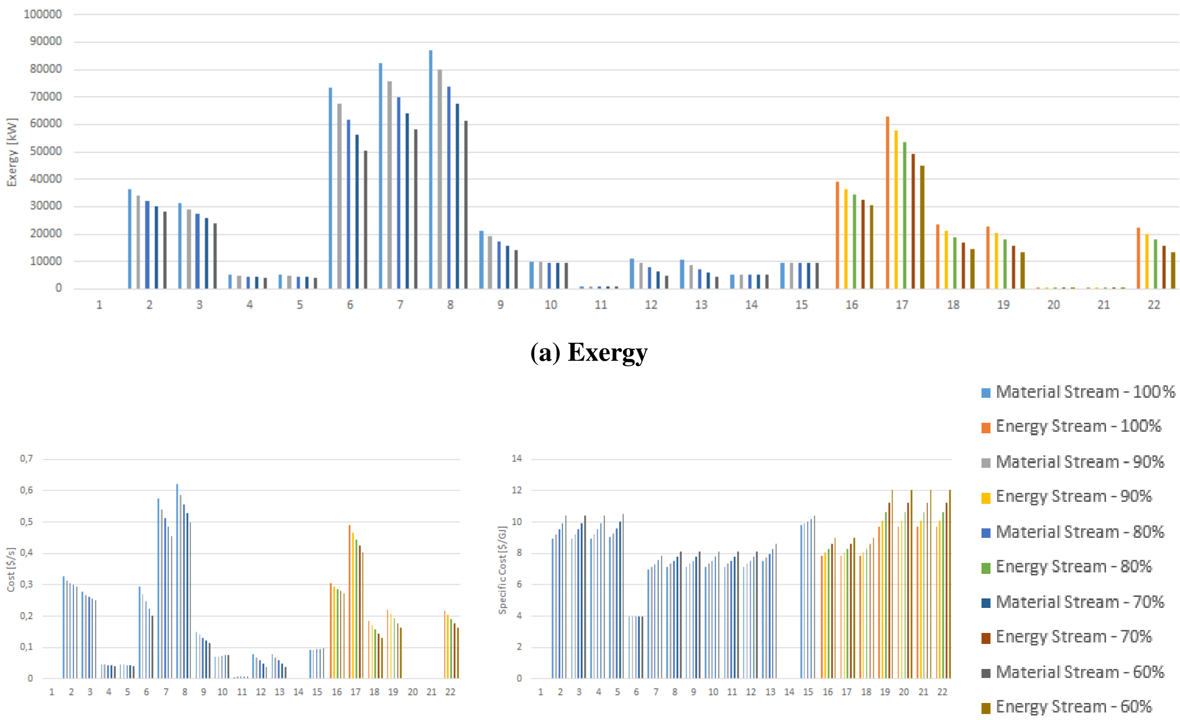
The price of the various equipments inside the gas turbine model was allocated based on suggestions made by Gomes (2001), and on the model price established Thermoflex®. The price of the heat exchanger is relative to the price of the gas turbine as well.

Table 5: Relative costs - Equipment

Equipment	Invesment cost$^{(1)}$ $[\%]$
Compressor	25.00
Combustion Chamber	4.09
Turbine	25.00
Recovery Heat Exchanger	37.45
Generator	45.91

$^{(1)}$ relative to the gas turbine

After obtaining the results, it is important to allocate the losses of the system (emissions) into the products. However, the exhaust gases' cost must be allocated into the products in two steps: in the first, the exhaust gases that go through the recovery heat exchanger must have their cost allocated into both electricity and process water based on the exergetic criterion, while in the second, the exhaust gases that are directly headed to the atmosphere must have their cost incorporated only into electricity. That sort of division is rational, and takes into consideration the destination of each of the flows.



(a) Exergy

(b) Cost **(c) Specific cost**

Figure 2: Fuel 1 - Main results

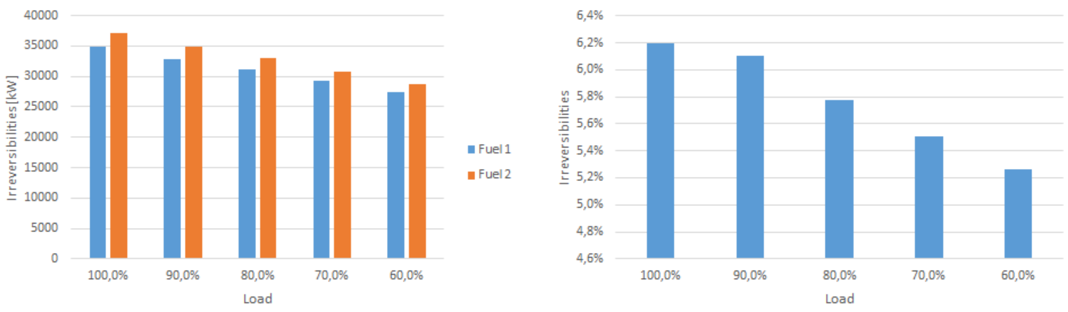
3 RESULTS & DISCUSSION

A broad view of the results obtained will be divided into two parts: in the first, the cogeneration plant will be analyzed exergetically and thermoeconomically, as previously mentioned, including electrical partial load conditions when the system is fed by a fuel gas of regular composition, and in the second these results will be compared with the ones obtained when the system is fed by a fuel gas with a very distinct composition from the first one, typical of pre-salt fields approaching their end of exploration: rich in CO_2.

Figure 2 shows the main results for the first system, representing the exergy, cost and specific cost of each flow considering the part-load variation, systematically organized as the legend suggests. Material streams relate to the order presented on Figure 1 and energy streams to Table 3.

From Figure 2a, it is seen that the material flows 6, 7 and 8 have the highest exergy, corresponding to the fuel, the exhaust gases leaving the combustion chamber and the exhaust gases entering the turbine, respectively; when it comes to the electrical flows, the turbine shaft power (flow 17) has the highest exergy because it is the origin of all the other electrical flows. Flows 14 and 15, corresponding to process water at inlet and outlet, respectively, do not vary with the load since the thermal demand is kept constant and independent from the electrical demand.

From Figure 2b, despite of what has already been highlighted before, flow 2 shows a high cost, since it corresponds to the flow leaving the compressor, which is fed by the highly exergetic compressor shaft power. Also, the costs of the flows 10, 11 and 15 are increased as load decreases, since the thermal load becomes continuously more representative relative to the electrical load.



(a) Irreversibilities for each fuel **(b) Relative variation - From fuel 1 to 2**

Figure 3: Fuels 1 and 2 - Irreversibilities

From Figure 2c, it is worth noting that the fuel specific cost is relatively small compared to the others, due to the high exergy of the fuel; it is constant because the fuel price is independent from the electrical load. The sum of the auxiliary powers and the net power correspond to the gross power, and every of these terms have the same specific cost due to the Theory of the Exergetic Cost's propositions; they have the highest specific costs due to the fact that they are the final products of the system and are responsible for a great part of the total exergy expense, but the high specific cost of the process water (flow 15) should also be pointed out.

When it comes to the comparison of the plant's outputs for the two different fuels, in terms of irreversibilities, as seen in Figure 3, the system ran by fuel 2 presents higher irreversibilities ranging from approximately 5.2 to 6.2 % compared to fuel 1, from the lowest to the highest electrical loads simulated; in terms of emissions, however, the difference is much higher as Figure 4 suggests, because fuel 2 has a significant CO_2 composition and higher mass flow compared to fuel 1.

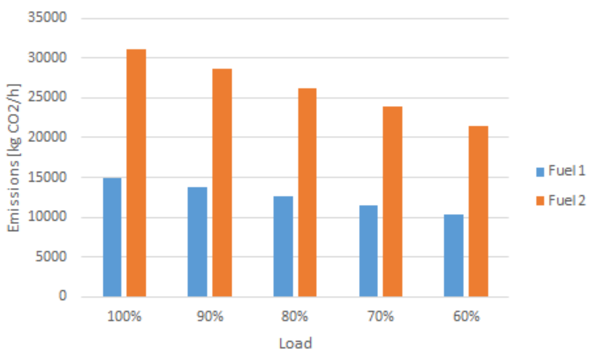
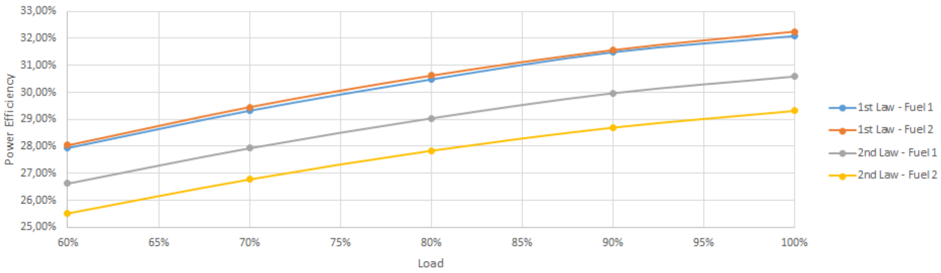
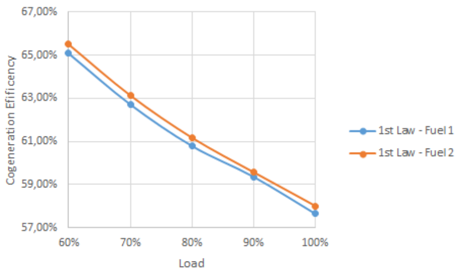


Figure 4: Fuels 1 and 2 - Emissions

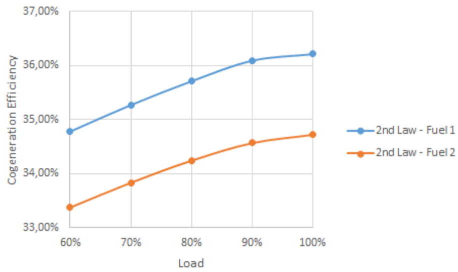
Figure 5 demonstrates that the system ran by fuel 2 has a higher 1^{st} Law efficiency, but a lower 2^{nd} Law efficiency. The 1^{st} Law efficiency was chosen based on the general equation for energy usage $\eta = \frac{\dot{W}+(\dot{H}_{out}-\dot{H}_{in})_{water}}{\dot{m}_f LHV}$, while the 2^{nd} is similar, but based on exergetic terms, thus $\epsilon = \frac{\dot{W}+(\dot{B}_{out}-\dot{B}_{in})_{water}}{\dot{B}_f}$. It is very important to distinguish the results taking into consideration both of these efficiency parameters, as it is seen ahead, because of the fact that they bring up different conclusions over which fuel is the most efficient, and contrasts the analysis often taken by the industry, based on the 1^{st} Law; using the 2^{nd} Law efficiency could be, therefore, more



(a) Gas turbine efficiency



(b) 1^{st} Law efficiency



(c) 2^{nd} Law efficiency

Figure 5: Exergetic comparison

reliable.

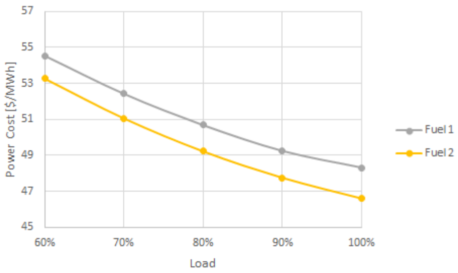
This trend was predicted by the higher $\frac{b_{ch}}{LHV}$ ratio shown in Table 4; it means that, even though the energetic efficiency of a system ran by fuel 2 is higher than the one ran by fuel 1, the exergetic efficiency scenario is the opposite, considering the same conditions. Also, it is interesting to notice that while the cogeneration 1^{st} Law efficiency decreases with the load, the 2^{nd} Law efficiency increases with it; that is explained because of the fact that both of the electrical efficiencies increase with the load, as it is expected, but while $\left|\frac{\partial \eta_{heat}}{\partial Load}\right| > \left|\frac{\partial \eta_{power}}{\partial Load}\right|$, we have $\left|\frac{\partial \epsilon_{heat}}{\partial Load}\right| < \left|\frac{\partial \epsilon_{power}}{\partial Load}\right|$, when $\frac{\partial \eta_{heat}}{\partial Load}$ and $\frac{\partial \epsilon_{heat}}{\partial Load}$ are negative because the thermal load is kept constant and the fuel mass flow is reduced together with the load, raising the efficiency of the heat recovery.

Fuel 2 is advantageous in economic terms, as it is seen in Figure 6. The specific costs of both electricity and process water are lower in this case, ranging from 2.6 to 3.6 % cheaper relative to the total specific cost.

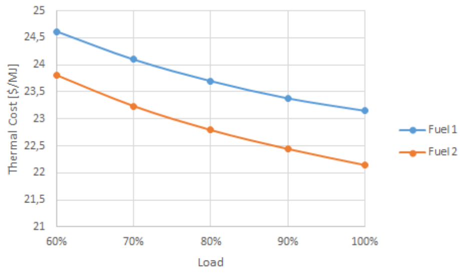
4 CONCLUSION

In conclusion, the cogeneration plant of the offshore platform was successfully characterized, both exergetic and thermoeconomically. The irreversibilites, emissions and flow costs of each system were obtained and compared between a system ran by fuels 1 and 2. The losses' exergetic costs were correctly allocated to the final products, resulting in an even higher cost for electricity because of two factors: electricity has a higher exergy than process water, and a substantial part of the exhaust gases are not recovered due to the relatively low thermal load.

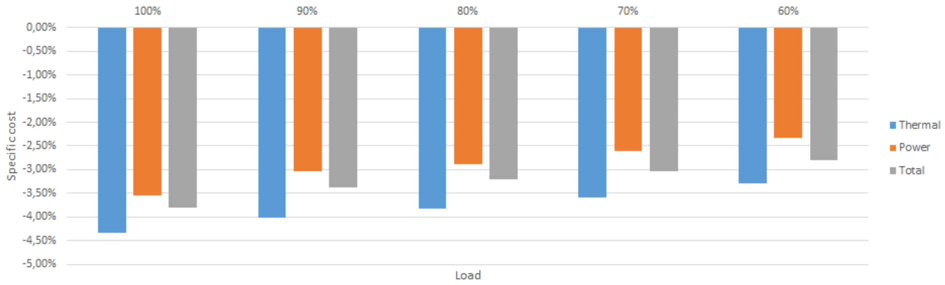
The system ran by fuel 1 has a higher exergetic efficiency, compared to the one ran by fuel 2, of around 1.5 %, therefore lower irreversibilites, and lower emissions. However, the latter



(a) Specific cost - Electricity



(b) Specific cost - Process water



(c) Relative variation - From fuel 1 to 2

Figure 6: Thermoeconomic comparison

is economically more attractive, as it was concluded through thermoeconomics. It is important to mention that the higher emissions may result in an environmental penalty, if applied, also higher, which could change this scenario economically, depending on the degree of legislation severity.

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