THERMOECONOMIC ANALISYS OF COGENERATION SYSTEMS IN OFFSHORE PLATFORMS – A CASE STUDY

Ulisses Admar Monteiro
Naval Engineer, Msc., DEnO/ UFRJ, Rio de Janeiro, RJ, Brazil
e-mail: ulisses@peno.coppe.ufrj.br

Carlos Rodrigues Pereira Belchior
Professor, Dsc., Mechanical Engineering, COPPE / UFRJ, Rio de Janeiro, RJ, Brazil
e-mail: belchior@peno.coppe.ufrj.br

Luiz António Vaz Pinto
Professor, Dsc., Ocean Engineering, DEnO/ UFRJ, Rio de Janeiro, RJ, Brazil
e-mail: vaz@peno.coppe.ufrj.br

Abstract *On offshore platforms, the cogeneration systems are used for electric and thermal generation simultaneously, to attend the demands of the Utility and the Process Plants. The use of those systems has been increasingly recognized, mainly for the possibilities of increasing the energy efficiency and for cost reduction. The electric power is produced in high scale for great consumers, and it can be exported to other offshore platforms. Additionally, thermal energy is of remarkable importance, especially in the separation of the oil-water-gas mixture. It becomes interesting to evaluate the production cost of those installations.*
The objective of this paper is to present a software for comparing several cogeneration systems, based on the knowledge of the electric and thermal demands of the platform.
The software performs a thermoeconomic analysis, consisting in a preliminary study, where the objective is to show the difference in the attractiveness of cogeneration, in function of the choice of the equipments, specially the gas turbines.

Keywords: *Cogeneration, Offshore Platforms, Thermoeconomic Analysis.*

1. Introduction

The low cost of the natural gas and its availability in the oil wells turns its use cost effective as the main fuel in offshore platforms, essentially when we want to eliminate the waste associated to burns of the "exceeding" natural gas. This burn can be considered as indication of the inadequate energy use, and shows the existent unbalance between available natural gas, extracted from the production wells, and the demands for that gas. It is used, basically, for gas lift, for the exportation through gas pipelines and as combustible.

The objective of this study is to present the development of a computational tool capable to propose, through input data (offshore platforms operational characteristics), the cogeneration system most suitable to the energy demands and it still offers the smallest total cost for final products (electricity and saturated steam). The analyses based on the methodology of thermoeconomic analysis (BEJAN et al., 1994).

Computational tool developed in LABVIEW® (National Instruments) calculates the costs of the electricity, of steam, besides, energy and exergy efficiencies of the selected cogeneration system. It also presents the economy of fuel cost obtained, when a cogeneration system is used instead of the isolated generation for electricity and steam.

Table 1. Nomenclatures

Nomenclature	**Subscripts**
T = Temperature (K)	i = ith flow stream in control volume
Q = Heat (KJ/Kg)	VC = control volume
W = Work (KJ/Kg)	k = cogeneration system component
m = Mass (kg)	d = property destruction
e = Specific Energy (KJ/kg)	p = products
E = Exergy (KJ)	f = fuel input
m_{gas} = Natural Gas Flow Rate (kg/s)	
PCI = Lower Calorific Value of the fuel (KJ/kg)	
e = Exergetic Efficiency	
Z = Cost related to a Cogeneration System component	

2. Cogeneration Systems Characteristics in Offshore Platforms

In offshore platforms we should consider some particularities in electric and thermal demands / production as the followings:

- ✓ Saturated steam is generated in the exhaust gas recovery boiler to produce hot water for pre-heating the oil-gas-water mixture before the process plant separator;
- ✓ The existence of many types of equipment in the Process Plants and Utility Plants requires that the ratios power / weight and power / space of the installation be considered.
- ✓ The natural gas explored in Brazilian offshore oil wells presents low Methane Number which is not increased in the offshore plant;
- ✓ The machines used for the electric power generation are required to operate in dual fuel (natural gas and diesel fuel) in order to have electric power generation in absence of natural gas, due to a offshore production pause;

3. Fundamentals

Thermoeconomic analysis, performed for three types of cogeneration systems, is based on exegetic balance of each component. For gas turbines, for instance, we consider each one of the main components: compressor, combustion chamber and turbine.

3.1. Exergetic Balance

For the control volume, in permanent regime, exergy variation inside of the control volume it is given by equation 1 (BEJAN et al., 1994).

$$0 = \sum_i \left(1 - \frac{T_0}{T_i}\right) \cdot \dot{Q}_i - \dot{W}_{VC} + \sum_e \dot{m}_e \, e_e - \sum_s \dot{m}_s \, e_s - \dot{E}_D \qquad (1)$$

Where the first and second member of the Eq. 1 is the exergy variation associated with the heat transfer. Second term is the transferred exergy, through the interaction work. Exergy flow input and flow output are given by the terms $\dot{m}_e \, e_e$ and $\dot{m}_s \, e_s$. Finally, E_d is exergy destruction due to the irreversibility in control volume. It can be calculated through the equation 2.

$$\dot{E}_D = T_0 \, \dot{S}_{gen} \qquad (2)$$

Where T_0 is the ambient reference temperature and $\dot{S}_{gen}$ is the entropy variation inside control volume.

For each component of the cogeneration system, the ratio of exergy destruction in relation to the total fuel that enters in the system, and in relation to the total destroyed exergy inside of cogeneration system are calculated in accordance with Eq. 3 and Eq. 4, respectively:

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \qquad (3)$$

$$y^*_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}} \qquad (4)$$

Where:

$$\dot{E}_{D,tot} = \sum \dot{E}_{D,k} \qquad (5)$$

And exergetic efficiency of each element, *k*, is given by Eq. 6.

$$e_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{6}$$

3.2. Economic Analysis

The thermal system design requires to estimate the total involved costs (total capital of investment, cost of fuel and expenses with operation and maintenance) assuming several considerations and predictions regarding the economical and technological aspects, using the engineering economy. References present economic aspects used in this paper.

3.3. Thermoeconomic Analysis

The thermoeconomic methodology used is the exergetic cost method (BEJAN et al., 1996). It involves costs formulated usually for each separately component.

This type of approach conduces to a different economical evaluation for the cost of electricity and steam, when compared to the traditional one, based on first law analysis. The aim of this methodology is to determine internal costs of the system component units.

For the costs of the k component of cogeneration system we must be consider the costs associated with exergy, the costs due to the investment, operation and maintenance. Then, for a component receiving heat transfer and generating power in permanent regime, we have the following equation (Eq. 7):

$$\sum_s \left(c_s \, \dot{E}_s \right)_k + c_{w,k} \, \dot{W}_k = c_{q,k} \, \dot{E}_{q,k} + \sum_e \left(c_e \, \dot{E}_e \right)_k + \dot{Z}_k \tag{7}$$

Where c_e, c_s, c_w and c_q are mean costs per exergy units (US$/GJ).

When one component is analyzed, it is assumed that are known all costs per exergy unit of the input flows in the system. Consequently, all the unknown variables will be calculated through the equation of costs (Eq. 7). Those unknown variables can be the costs of the power and steam produced. The method of the extraction was considered in the calculation of the electricity cost.

3.4- Cogeneration System Efficiency

Besides the thermoeconomic criteria presented in the previous item, the efficiency of the cogeneration system is an important criteria for evaluating the energy utilization of the system. Therefore, the computational tool, calculates the efficiency of the cogeneration system, based on three (3) requirements.

The criteria used for the calculation will be presented in next item, together with some comments on the advantages and drawbacks of each one of them, in agreement with FENG et al. (1998) and NEBRA (2002).

3.4.1- Energy Efficiency

Energy Utilization Factor (EUF) can be defined by the Eq. 8:

$$EUF = h_{COG} = \frac{\left(\dot{W} + \dot{Q} \right)}{\dot{m}_{GN} \cdot PCI} \tag{8}$$

Where W is the electric power produced by cogeneration plant; Q is the produced useful heat; and ($\dot{m}_{GN} PCI$) is the energy of the fuel (natural gas) used in cogeneration plant.

EUF has the advantage of being simple. However, it doesn't allow discrimination between W and Q (or between Q produced in different temperatures).

3.4.2- Fuel Economy Ratio

This criteria for evaluation of cogeneration systems involves a comparison between the necessary fuel to fulfill the thermal and electric load requirement, with those that would be required in a isolated conventional plant, i.e., in a plant of generation of electric power of total efficiency h_W and in an boiler whose efficiency is h_{CA}. Then, the energy of the fuel saved is given by the Eq. 9:

$$\Delta \dot{E} = \left[\frac{\dot{Q}}{h_{CA}} + \frac{\dot{W}}{h_{W}} \right] - \dot{m}_{GN} \cdot PCI \qquad (9)$$

FER is defined as the ratio between the fuel energy saving and the fuel required by the conventional plants, according to the Eq. 10.

$$FER = \frac{\Delta \dot{E}}{\left[\frac{\dot{Q}}{h_{CA}} + \frac{\dot{W}}{h_{W}} \right]} \qquad (10)$$

FER denotes the value of fuel energy saving of the cogeneration plant. Therefore, it is a reasonable criterion. However, we must consider that it does not take into account, the cost of the heat and the electricity in the plant.

3.4.3- Exergetic Efficiency

The exegetic efficiency of a cogeneration system that produces power and thermal energy is given by the Eq. 11.

$$e_{COG} = \frac{\dot{W} + \Delta \dot{E}}{j \cdot PCI \cdot \dot{m}_{GN}} \qquad (11)$$

Where the factor φ allows calculating the exergy of the fuel by its PCI (KOTAS, 1985) and $\Delta \dot{E}$ is the variation of the exergy of the water used in the boiler to produce saturated steam.

Exergetic efficiency acts as a base for comparisons among cogeneration systems (of the same type) with different capacities of electricity and heat production, due to the fact that the exergy quantify the difference in the quality of the heat produced in different temperatures.

4. Cogeneration System Selection

The methodology for the selection of the cogeneration system was divided in four stages:

1. Analysis of the energy demands;
2. Method of selection of the cogeneration cycle with Gas turbines;
3. Method of selection of Cogeneration System using Rankine Cycle;
4. Method of selection of Cogeneration System using Combined Cycle;

4.1. Offshore Platforms Demands

The thermal and electric demands profile is of fundamental importance for definition of the appropriate cogeneration system. In that sense, it is necessary to know the curves of typical demand, including the more critical operational conditions of the platform (loading or off-loading, for instance), where it is possible to identify maximum and mean values of the demands.

Although it is necessary that the system supply the maximum electric demand, it won't be selected only considering this operation point. Then, a base load is determined. It represents the demand point where the system will operate in most of the time. This way, it is required that the cogeneration system presents maximum efficiency in the base load and has minimum deviations in other typical operational points.

The computational tool, when performing thermoeconomic analyses, takes into account the following considerations:

1. Determination of energy demand (electric and thermal);
2. Definition of the operational points;
3. Electric power priority;
4. Fulfill the thermal demand required;

4.2. Gas Turbines and Exhaust Gas Boiler

The methodology for selection the cogeneration system follows the stages:

1. For each Gas turbine, available in database, the produced power is calculated considering the environmental conditions of operation, selecting the options that fulfill the necessary electric demand;

2. The saturated steam production is calculated in function of exhaust gases flow and temperatures. Additional burns of fuel is allowed to fulfill the thermal demand;
3. Exhaust gas boiler is selected in order to fulfill the thermal demand;
4. An exergetic analysis is performed (for gas turbine + Exhaust gas boiler);
5. An economical analysis is performed for the selected groups (including methods of investment analysis such as Net Present Value);
6. A thermo-economical analysis is performed, selecting the equipments that presents the lower total cost of the products;
7. For the cogeneration system selected in the item 6, the technical data are presented (including equipment type, manufacturer, fuel consumption, operational efficiency of the Gas turbine, efficiency of the cogeneration system, etc.) and economical data (estimate of the initial cost, fuel cost, operational and maintenance costs, electricity and steam produced costs, etc).

Figure 1 shows the Gas Turbine Cogeneration Cycle.

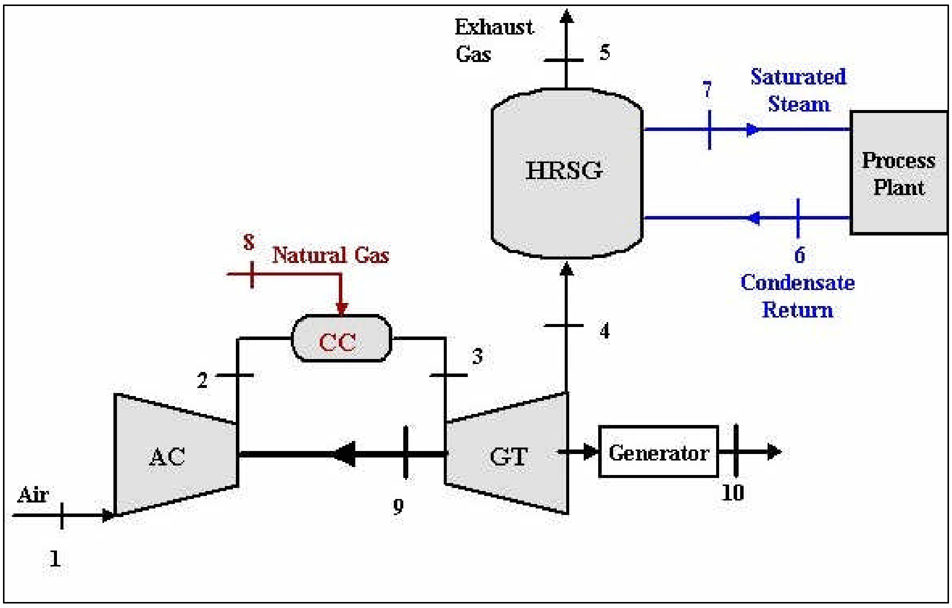

Figure 1. Gas Turbine Cogeneration Cycle

4.3. Rankine Cycle and Combined Cycle

Rankine Cycle analysis was simplified according to HARRINGTON (1992) recommendations. For electric power production, pressures of 21 kgf/cm^2, 42 kgf/cm^2 and 62 kgf/cm^2 are used in the turbines of multiple stages.

When the gas turbines exhaust gases present enough energy to be recovered in a steam turbine, a combined cycle can be used. Around 20% to 35% of the total demand of electricity can be supplied by the Steam Turbine, with the consequent reduction in the fuel consumption. As this is the main objective of the Combined Cycle, in this case, it is not allowed the use of supplemental burns to supply the thermal demand of the platforms.

The main objective of this thermoeconomic analysis is to select the lower total cost plant, including the gas turbine, exhaust boiler and steam turbine. Figure 6 shows the Rankine Cycle.

5. Case Study

In order to present the software, it will be selected the most suitable cogeneration system that fulfill the requirements of the operational characteristic of the petroleum production unit of the semi-submergible platform P-40. The choice of that unit is due to the fact that the electric and thermal demands are known, and also the operational parameters of the equipments that supply those demands.

The P-40 offshore platform operates with 3 compressors driven by gas turbines, but the Petrobras already decided that in the future, the compressors will be driven by electric motors in the new platforms projects. For that reason, we decided that all electric and thermal demands are supplied by the cogeneration plant.

Table 2 summarizes the operational data similar to those of the platform.

Table 2: Semi-submergible Platform P-40 - Operational Data

Operational Condition	**Data**
Maximum Electrical Demand	22.250 kW
Mean Electrical Demand	20.000 kW
Mean Thermal Demand	41.300 kW
Operational Period	8760 h/year
Environmental Conditions	
Pressure	1,013 bar
Temperature	35 ^oC
Relative Humidity	80 %
Economical Data	
Expectancy Life	20 years
Interest rate	12 % per year.
Natural Gas Production Cost	0,03 US$/m^3

The computational tool analyzes the three types of cogeneration system with potential to fulfill the energy demand of the platform. The choice is due to technical and economical factors.

Figure 2 shows the screen with the input data for the analysis of the case of study. As it can be seen, the software allows evaluating each cogeneration cycle separately. Then, it is possible to perform a thermoeconomic analysis for a particular cycle. Alternatively, it is also possible just to select the cogeneration cycle of smaller total cost, selecting the option "Global Analysis". This way, just the cycle results will be presented in the screen.

Operational parameters including in Fig. 2 were obtained from P-40 thermal and electric demands.

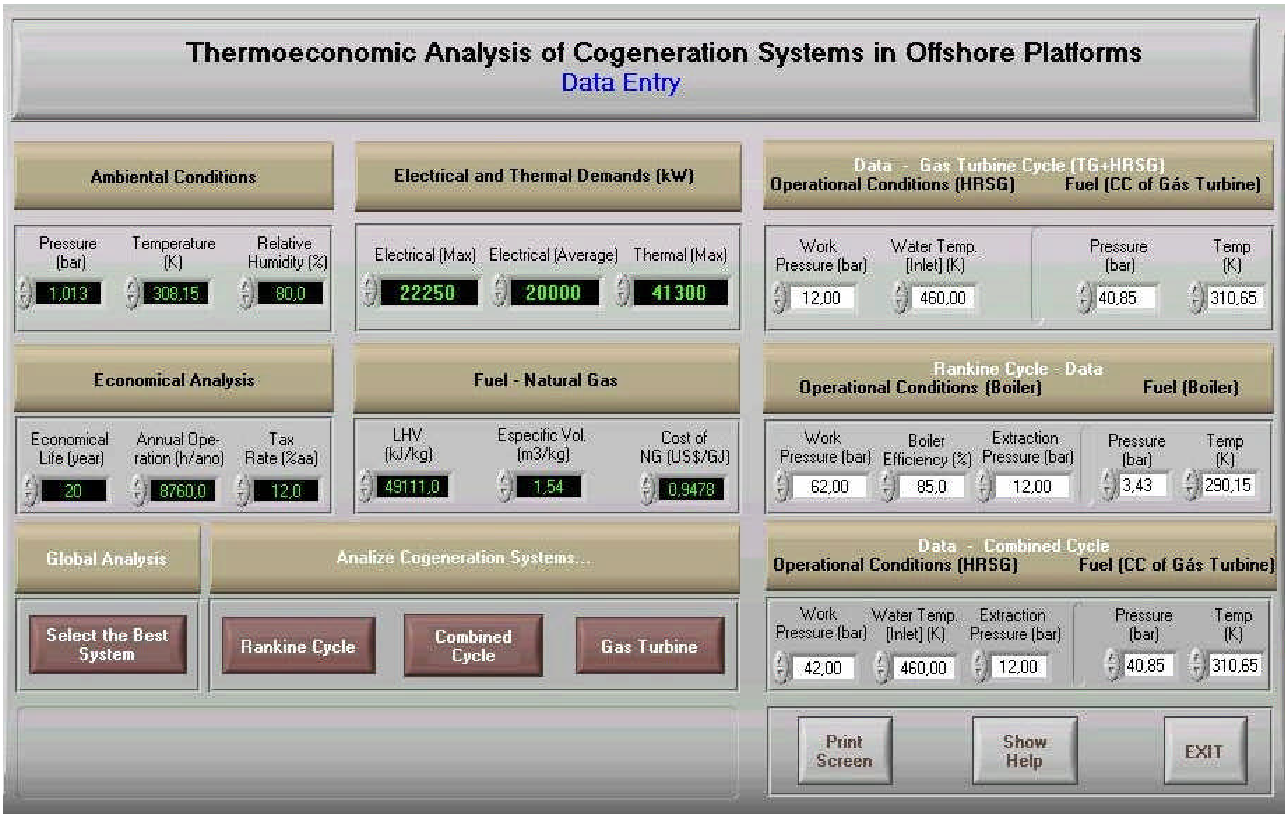

Figure 2. Operational Parameters Input Data

5.1. Cogeneration System Analysis – Gas Turbines and Exhaust Gas Boiler

When executing the program to analyze the cogeneration system with Gas turbines and Exhaust Gas Boiler the turbo-generator selected was GE LM 2500PK whose ISO power is 30900 kW. However, due to the influence of the environmental conditions, the maximum power that the turbine can produce, according to the environmental local conditions, is 27797 kW, according to Fig. 3.

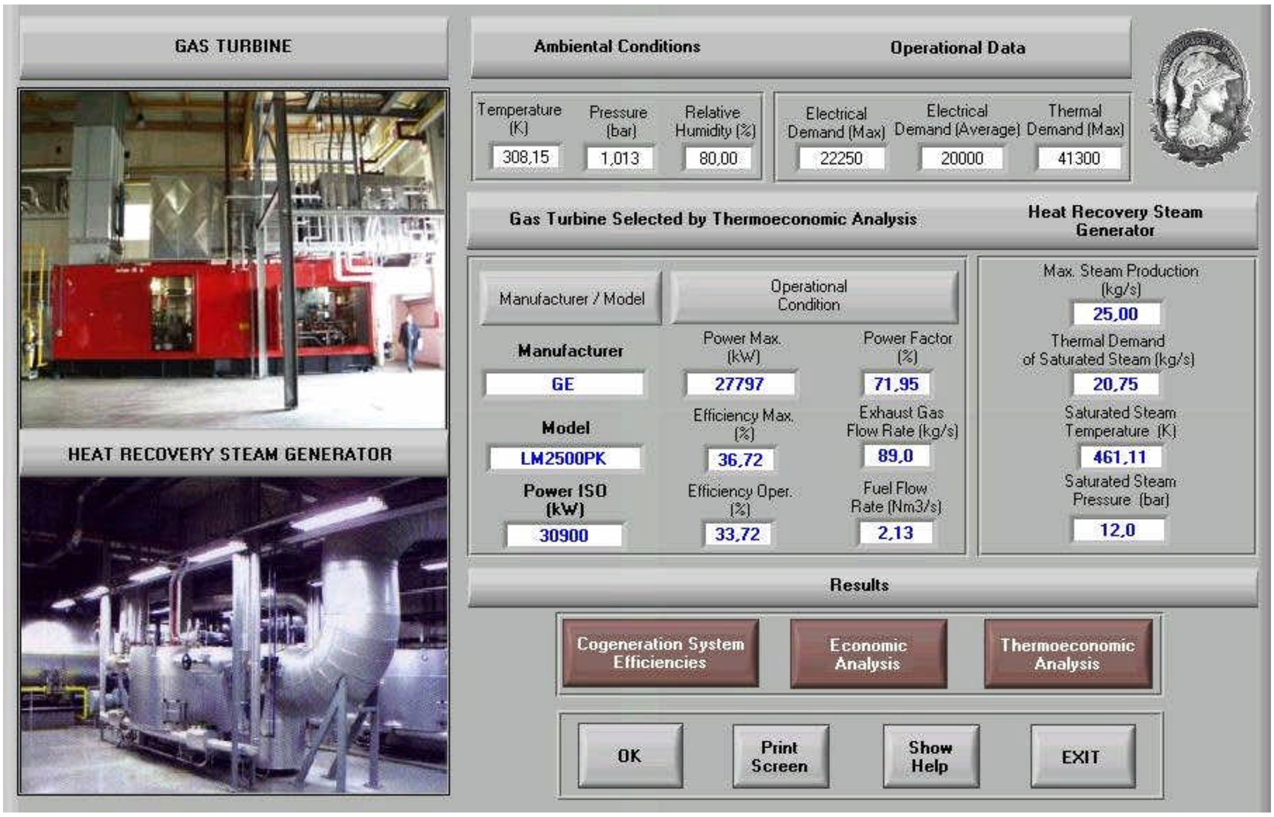

Figure 3. Gas Turbine + Exhaust Gas Boiler Technical Data

Figure 4 shows the energetic and exergetic efficiencies. The efficiency calculated by the thermodynamic First Law shows that 86.5% of the input energy in the system is transformed in work, while the exergetic efficiency shows that only 46.4% of the exergy that enters in the system with the fuel are really used.

Figure 4 still shows a comparison between Gas Turbine / Exhaust Gas Boiler cogeneration system and an isolated system for electricity and steam production. It can be seen that the economy of fuel of the cogeneration system, in relation to isolated system, reach 34.4%. In economical aspects, this save reach to 126.48 US$/h, for a cogeneration system working 24 hours by day, which is the case of Petroleum Production Units.

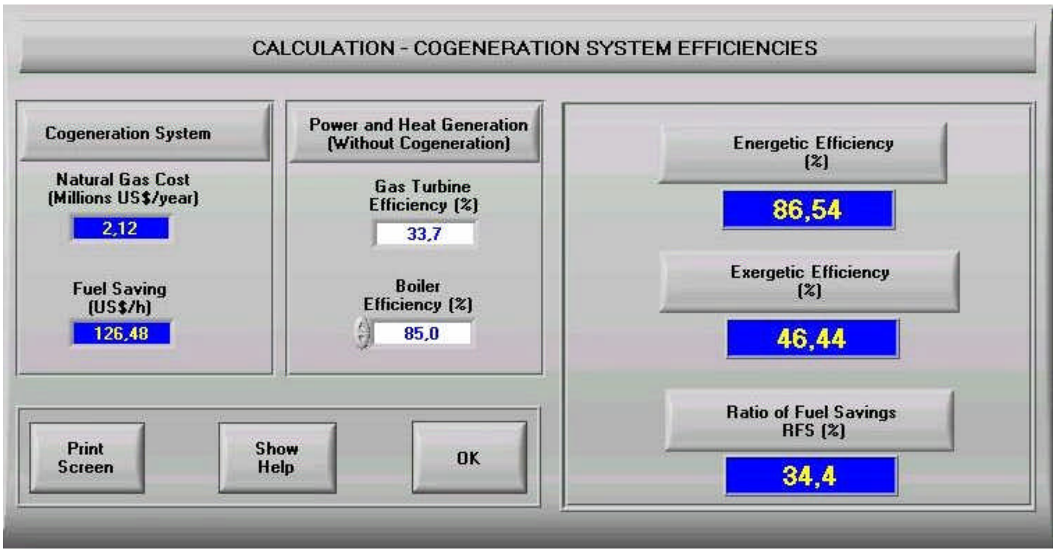

Figure 4. Energetic and Exegetic Efficiencies Results

Figure 5 shows the costs of production of the saturated steam and electricity. It can seen that the cost of electricity is 128.00 US$/h or 6.4 US$/MW.h. The cost of steam is 129.78 US$/h or 0.0017 US$/kg.

The high steam cost per hour is due to the great thermal demand of 41.3 MW that needs to be supplied by the cogeneration system. It should be noted that was necessary to use supplementary fuel in Exhaust Gas Boiler to fulfill the thermal required demand.

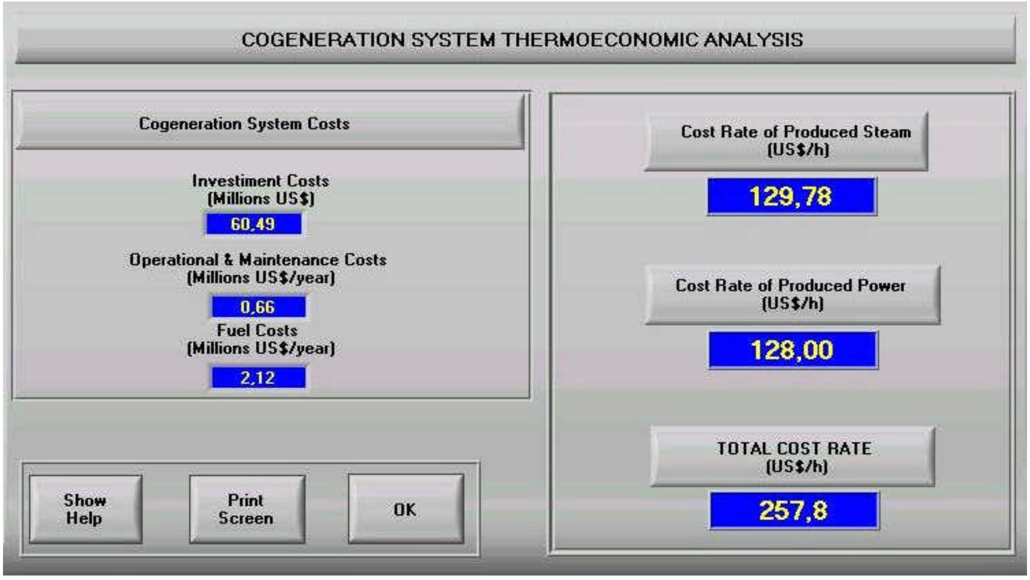

Figure 5. Thermoeconomic analysis results

5.2. Rankine Cogeneration System Analysis

According to Fig. 6, the Rankine Cycle used in this thermoeconomic analysis operates with a pressure of 62 bar and, this way, exergetic efficiency of the cycle reach 37.07%. It can be seen that the efficiency of the cogeneration system based on the First Law is 61.63%. This value is due fundamentally to high steam production. By other side, Rankine Cycle thermal efficiency is only 20.11%.

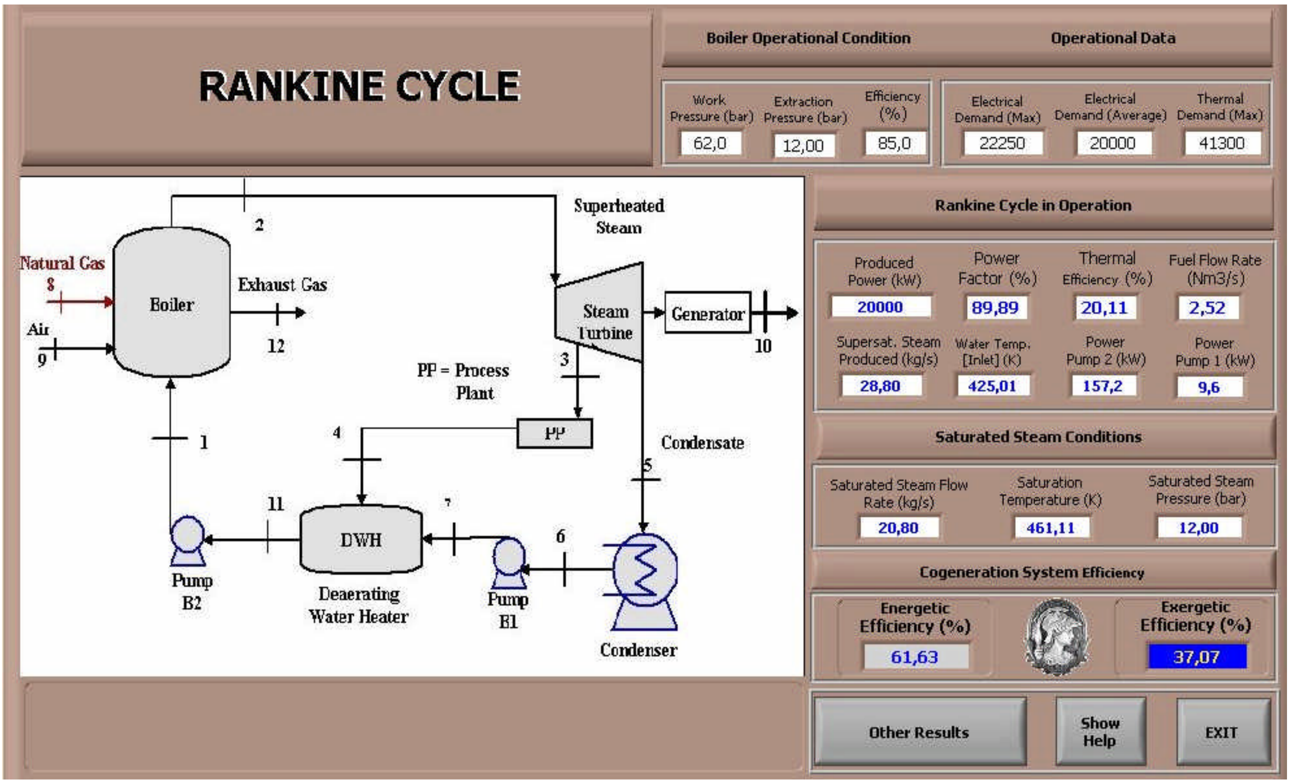

Figure 6. Rankine Cycle Technical Data

Thermoeconomic analysis shows that the electricity production cost is 222.93 US$/h or 11.15 US$/MWh, and saturated steam production cost is 214.73 US$/h or 0.0029 US$/kg, as shown in Fig. 7.

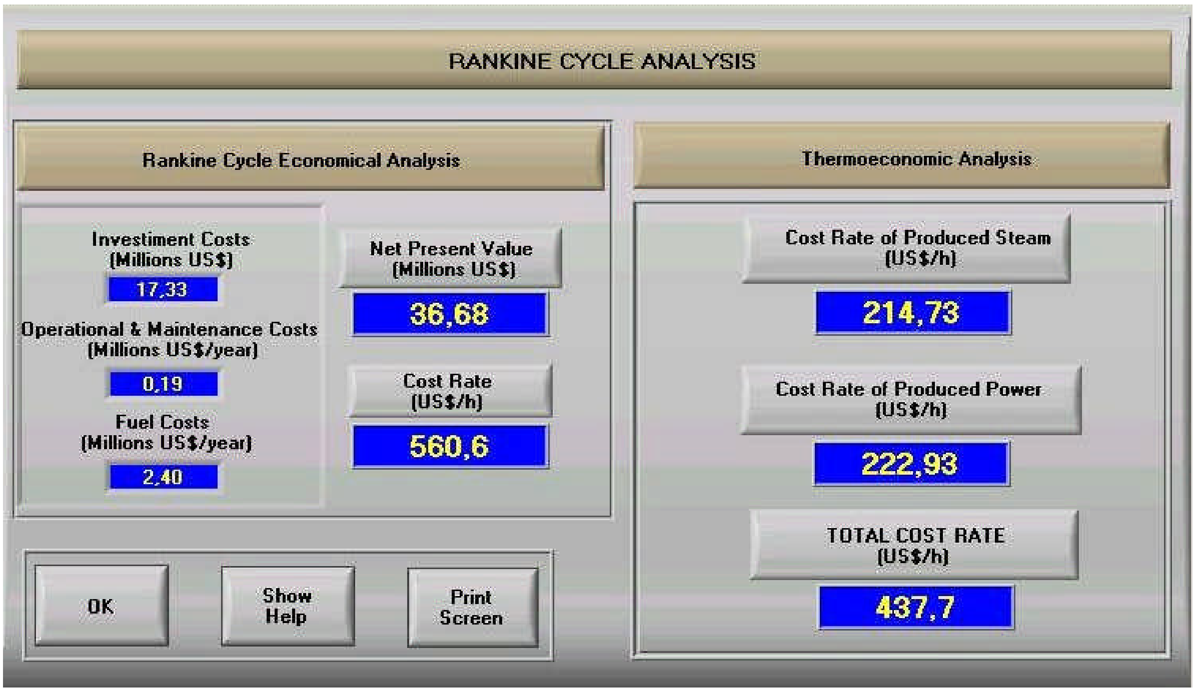

Figure 7. Rankine Cycle Results

The exergy destruction present in the boiler is especially due to the combustion process and for the heat transfer due to the finite difference temperature between the exhaust gases and the water. But, for the case study, the exergy destruction in the Steam Turbine, near the place where the final product is generated, is the responsible for the high cost of the products. More details on the exergy destruction influence in the process of cost formation are given in BEJAN et al. (1994).

Table 3 shows a comparative results of the two cogeneration systems of Fig. 5 and Fig. 7, to operate in the P40 Platform. It can be observed that the gas turbine + exhaust gas boiler cogeneration system presents the lower cost of the products, and a total cost of 258.7 US$/h against 437.7 US$/h of the Rankine Cycle.

Table 3: Cogeneration System Possibilites

Cycle	NPV (Million US$)	Cost of Electricity (US$/h)	Cost of Electricity (US$/MWh)	Cost of Steam (US$/h)	Cost of Steam (US$/h)
Rankine	36.68	222.93	11.15	214.73	0.0029
GT / EGB	76.25	128.00	6.40	129.78	0.0017

5.3. Combined Cycle Analysis

A thermoeconomic analysis was not performed using the Combined Cycle, due to the high thermal demand it is not possible, using the gas turbines from database, to generate superheated steam enough to produce electricity in the steam turbine and to extract saturated steam for the Process Plant.

Since one of the objectives of the Combined Cycle is to use the energy in the exhaust gas of the gas turbine in order to reduce the costs with fuel, it was not allowed the use of supplementary fuel to complement the steam production and then to fulfill the thermal demand.

6. Conclusion

It was verified that, in agreement with several simulations executed by software, the thermoeconomic analyses indicated the use of gas turbine cogeneration system, which is a tendency when the electric and thermal demands are high, as it happens in new petroleum production units projects.

A suggestion for improvement of the analyses is the evaluation of the histograms of electric and thermal loads of the platforms, during several years of production, in order to define the best operational point and the number of equipments that assist to the electric demand.

Another recommendation is to study the use of the refrigeration unit through the absorption cycle in cogeneration system, taking advantage of the hot water that returns from the separation equipment, after heating up the mixture of oil-water-gas coming from the well. This cooling can be used as to reduce the air inlet temperature in compressors of turbo-generators or in air conditioning system of the living quarters.

6. Aknowlegment

The authors thank ANP (National Agency of the Petroleum) for the financial support, fundamental for this research and National Instruments that do available the license of the LabVIEW software.

7. References

BEJAN, A., TSATSARONIS, G., MORAN, M., 1996, “Thermal Design and Optimization”, 1 ed. New York, John Wiley & Sons, Inc.

FENG, X., CAI, Y., QIAN, L., 1998, ”A New Performance Criterion for Cogeneration System”, *Energy Conversion &. Management*, v.39, n.2, pp.1607-1609.

HARRINGTON, R.L., 1992, “Marine Engineering”, 2 ed. New Jersey, The Society of Naval Architects and Marine Engineers.

KOTAS, T.J., 1985, “The Exergy Method of Thermal Plant Analysis”, 1 ed. London, Anchor Brendon Ltd.

NEBRA, S.A., 2002, “Sistemas de Cogeração: Métodos de Avaliação”, *II Congresso Nacional de Engenharia Mecânica*, João Pessoa, PB, 12-16 de Agosto.

SAMANEZ, C.P., 2002, “Matemática Financeira: Aplicações à Análise de Investimentos”, 3 ed. São Paulo, Prentice Hall.

SILVEIRA, J.L., TUNA, C.E., 2003, “Thermoeconomic Analysis Method for Optimization of Combined Heat and Power Systems. Part I”, In: Progress In Energy and Combustion Science, Science Direct (www.sciencedirect.com).

TSATSARONIS, G., PISA, J., 1994, “Exergoeconomic Evaluation and Optimization of Energy Systems – Application to the CGAM Problem”, Energy, v.19, n.3, pp. 287-321.