METHOD FOR ANALYSING THE COMPOSITION OF THE ELECTRICITY COST GENERATED IN GAS-FIRED COMBINED CYCLE PLANTS

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Abstract. *The proposal of the method for analyzing the composition of the electricity cost is based on the energy conversion processes and destruction of the exergy contained in the fuel through the several thermodynamic processes that comprise a combined cycle power plant. The method uses thermoeconomics to evaluate and allocate the cost of exergy degradation throughout the processes, considering the costs related to the used inputs and equipment.*

Although the concept may be applied to any combined cycle power plant or cogeneration one, this work develops only the mathematical modeling for three-pressure heat recovery steam generator configurations and total condensation of the produced steam. It is possible to study any n x 1 plant configuration (n trains of gas turbine and heat recovery steam generators associated to one steam turbine generator and condenser) with the presented model, since every train operates identically and in steady state.

The presented model was conceived from a complex configuration of power plant, over which variations may be applied in order to adapt it to a defined configuration under study. The variations and adaptations include, for instance, use of reheat, supplementary firing and partial load operation, besides sensibility analysis on geometrical equipment parameters.

Keywords*: Thermoeconomics, exergy, power plant, natural gas*

1. Introduction

The objective of this work is to present a methodology that allows calculating costs of the electricity generated in combined cycle power plants, in a variety of configurations, technologies and operation conditions, relating the energy cost of the outputs to the thermodynamic processes that surround them. The efficiency of such processes in transforming the potential of the natural gas as an energy source into work, later converted into electricity, is analyzed aiming at to reach optimum situations, from the economic and technical points of view.

As tools for the study of the processes that comprise a combined cycle power plant, the proposed method includes, beyond the fundamentals of the thermodynamics and heat transfer, the concept of exergy and its applications in thermoeconomics. The additional costs of operation and maintenance, transmission, taxes and others are not included in the scope of this study, since they are not directly related to the energy conversion processes. Their relevance for the general evaluation of the costs of the electricity is recognized, however their non-energy nature separates them from the basic premise of this work

2. Exergy and Thermoeconomis

2.1. Introduction

Exergy suffers alterations during the occurrence of determined process, being destroyed by the generation of irreversibility. This way, value can be attributed to a stream, based on its energy content. A thermoeconomic balance shows the variation in the quality of energy, attributing to it an exergy-based cost that can be altered according to the precedence of the stream, its interactions with thermodynamic processes and the cost of the equipment in which these processes occur.

In order to formulate the thermoeconomic balances, the studied systems are divided in control volumes or sub-regions, defined by inlet and outlet streams. Each control volume is examined and modeled in such a way that a linear system of equations is formed and a single solution that satisfies it can be obtained. The sub-regions may contain several equipment and process inside its boundaries; however, for this study each sub region will contain only one equipment and in some cases equipment are divided in smaller control volumes in order to study the cost distribution through the processes until the electricity generation is reached.

For a given sub-region that contains equipment X, with i inlet streams and j outlet streams, the thermoeconomic balance is show in Equation (1).

$$\sum_{m=1}^{i-1} B_{inlet}^{m} c_{inlet}^{m} + W_{inlet}\ c_{inlet}^{m} + \dot{Z}_X = \sum_{n=1}^{j-1} B_{outlet}^{n} c_{oulet}^{n} + + W_{outlet}\ c_{outlet}^{W} \quad (1)$$

The costs in exergy-base of streams B are in most of the cases the variables of the system. The application of thermoeconomic balances show in Equation (1) for a control volume with n sub-regions results in Equation (2).

$$\left[\dot{B}\right]_{n\times n} \times \left[c\right]_n = \left[\dot{Z}\right]_n \quad (2)$$

However, the thermoeconomic balances are defined for each sub-region, and so a control volume with n sub-regions results in a system with n variables but not necessarily n equations. In order to find a single solution to Equation (2), defining criteria that establish relation among certain variable is necessary.

The extraction criterion considers that generation power is the ultimate objective of a turbine. Therefore all other capital and irreversibility costs are allocated in the product, that is, the electrical/mechanical power, in such a way that the inlet and outlet streams are assigned the same specific exergy-based cost The equality criterion considers, besides the power, the stream that leaves the turbine also as a product; consequently both products share the same exergy-based specific cost. (Kotas, 1987 / Silva, 2004)

Other criteria will be applied to determined equipment, with the objectives of detailing the composition of the electricity cost and providing a manner to distribute costs according to the exergy content of each stream.

Once the criteria are applied, any computational tool can be used to obtain the solution to the linear equation system shown in Equation (2).

2.2. Method description

The model presented in this work was conceived from a complex power plant configuration depicted in Figure (10), over which several variations can be done to adapt it to a determined configuration to be studied,. The variations and adaptations include, for instance, reheating, supplementary firing and partial load operating and also sensibility analysis of equipment geometry.

The first step is to collect information on the power plant configuration in study, detailing equipment and their capacities, transport properties of each process stream, consumed and generated power. The data that define each stream, that is, mass flow, temperature, pressure, enthalpy, entropy and consequently entropy may be collected using many different sources. One usual source is a computerized process simulator; nevertheless data from the digital control system of operating plants and information from engineered heat balances also provide the necessary information.

The next step comprises using the equipment capacity to estimate costs, using a parametric method which calculates an estimated cost based on a reference biome of cost and capacity (Bohem, 1987).

Finally, the linear equation system is obtained, and from the solution of Equation (2), results a vector containing exergy-based costs for each stream. From this point on, several plant characteristics may be altered, which will ultimately recalculate matrix B and vector Z of Equation (2), and therefore result in a new exergy-based cost vector. Improving the power plant performance depends on defining which values from this vector are to be optimized and thus seeking alterations that will produce the desired effect. Figure (1) illustrates the proposed method.

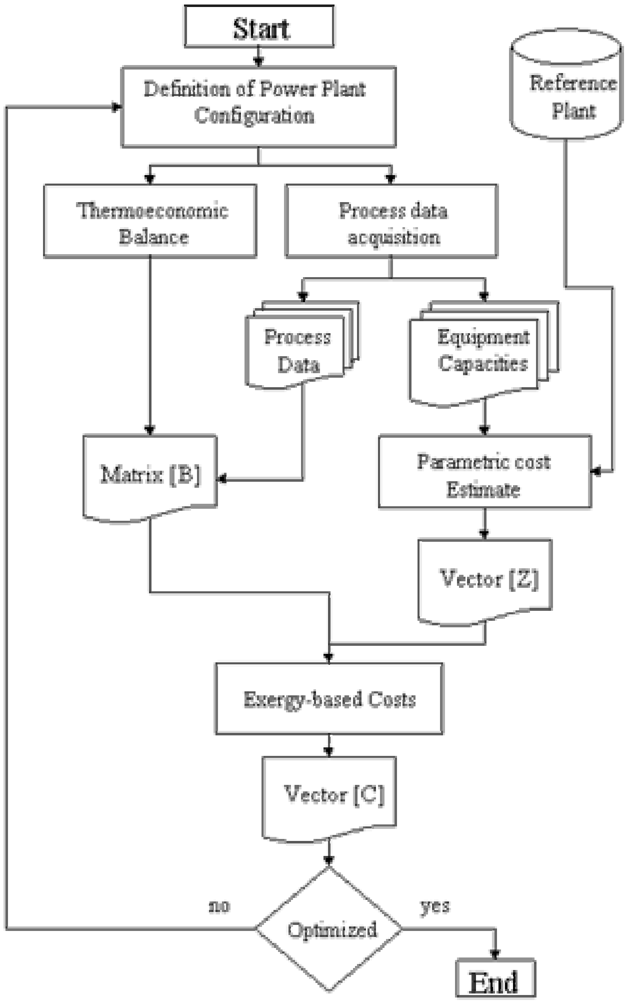

Figure 1. Flowchart depicting the proposed method. (Borelli,2005).

2.3. Cost allocation criteria for the Heat Recovery Steam Generator

The exhaust gases from the combustion turbine have monetary value, in terms of thermoeconomics, because the steam that turns other turbines is generated from them. However, in the exhaust stack the same gases have no longer a use as far as the power plant is concerned, and for that reason cannot be assigned a value. Assuming otherwise, like applying the extraction criterion, would leave certain costs unallocated and thus produce an artificially lower cost for the generated electricity (Gomes, 2001). On the other hand, assigning a zero-value to the exhaust stream discharges all costs in the boiler feed water, penalizing the steam generation in non-uniform basis (Silva, 2004).

As there is use for the exhaust gas from the combustion turbines and from the supplementary firing modules and hence these streams are assigned a cost, and the boiler stack exhaust must contain a null monetary value, it is necessary to propose a criterion to distribute the costs through the several modules of the heat recovery generator, taking into consideration the exergy essence of each stream and its variation.

The proposed variation law is shown in Equation (5), in which C represents the exergy-based cost of the exhaust gases and ΔB the difference between the exergy essence of the same gases in the entrance and exhaust of the heat recovery boiler. Index i refers to each module of the boiler and n to the last on before the exhaust stack (Borelli, 2005)

$$C_i = \left(1 - \frac{\Delta B_i}{\Delta B}\right) C_{i-1} + \left(\frac{\Delta B_n}{\Delta B} - 1\right) C_{n-1} \qquad (5)$$

3. Results

Table 1 brings results of comparisons made using 1x1 power plants using several combustion turbines technology, a first application of the method. The configuration of the heat recovery boiler is similar for every simulation, and it contains three pressures and three modules in each pressure level, and no reheating. It was allowed to the simulator to adjust the modules within a range of geometrical characteristics to obtain best results for each configuration.

Table 1: 1x1 Combustion Turbine study

Combustion Turbine model		SWPC 501G	ABB GT24	SWPC 501FD	GE PG7421FA	SWPC 501DA	GE PG9171E
Combustion Turbine power	MW	212,73	167,61	168,07	157,52	109,85	112,84
Plant Power	MW	311,11	247,21	249,47	239,63	166,49	172,52
Combustion turbine exergetic efficiency		0,36	0,35	0,35	0,34	0,32	0,31
Power Plant exergetic efficiency		0,53	0,52	0,52	0,51	0,49	0,48
High Pressure Steam Turbine Power	MW	29,02	23,94	23,91	24,25	14,82	15,82
Intermediate Pressure Steam Turbine Power	MW	27,69	22,54	22,97	23,14	16,27	17,12
Low Pressure Steam Turbine Power	MW	41,66	33,11	34,52	34,72	25,55	26,75
Installation Costs*	US$/kW	324,67	314,05	336,39	348,70	385,16	382,63
Electricity Cost – Combustion Turbine	US$/MWh	17,60	17,18	17,72	17,59	18,23	18,51
Electricity Cost – High Pressure Steam Turbine	US$/MWh	41,86	42,26	42,68	42,58	47,61	47,07
Electricity Cost – Intermediate Pressure Steam Turbine	US$/MWh	45,17	45,42	45,88	45,82	50,84	50,23
Electricity Cost – Low Pressure Steam Turbine	US$/MWh	61,47	61,50	62,52	62,48	66,45	66,01
Electricity average cost	US$/MWh	28,20	28,12	28,90	29,35	31,43	31,64

(*) Installation costs presented are referred to power island only (Gas Turbine World Handbook, 2005)

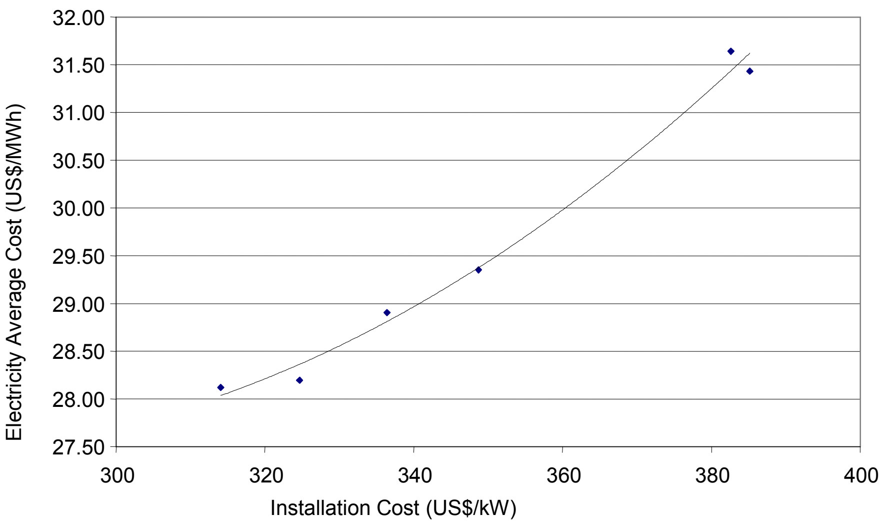

Figure 2. Installation cost study.

By analyzing Table (1) and Figure (2), one can notice the relation between exergetic efficiency and the average cost of electricity. The comparison between a plant based on ABB GT24 machine and another based on a SWPC 501G shows that the installation cost may sometimes compensate a lower efficiency.

A deeper analysis on Table (1) allows the study of the composition of the average cost as a function of the costs calculated in each generator. The lower value is related to the combustion turbine generator for all cases, hence, including more combustion turbine in 2x1 or 3x1 configurations results in lower average costs. Table (2) shows results obtained by varying the number of ABB GT24 machines in the power plant.

Table 2: N x 1 configurations study

Configuration		1 x 1	2 x 1	3 x 1
Combustion Turbine power	MW	167,61	167,61	167,61
Plant Power	MW	247,21	490,12	567,96
Combustion turbine exergetic efficiency		0,35	0,35	0,35
Power Plant exergetic efficiency		0,52	0,52	0,52
High Pressure Steam Turbine Power	MW	23,94	49,28	74,63
Intermediate Pressure Steam Turbine Power	MW	22,54	44,98	67,42
Low Pressure Steam Turbine Power	MW	33,11	66,05	98,99
Installation Costs*	US$/kW	314,05	257,17	221,92
Electricity Cost – Combustion Turbine	US$/MWh	17,18	17,17	17,17
Electricity Cost – High Pressure Steam Turbine	US$/MWh	42,26	38,84	37,51
Electricity Cost – Intermediate Pressure Steam Turbine	US$/MWh	45,42	42,69	41,65
Electricity Cost – Low Pressure Steam Turbine	US$/MWh	61,50	47,22	43,11
Electricity average cost	US$/MWh	28,12	25,65	24,88

(*) Installation costs presented are referred to power island only (Gas Turbine World Handbook, 2005)

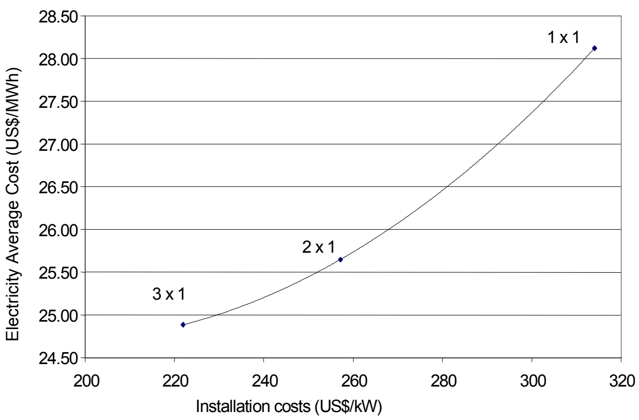

Figure 3. N x 1 configuration study

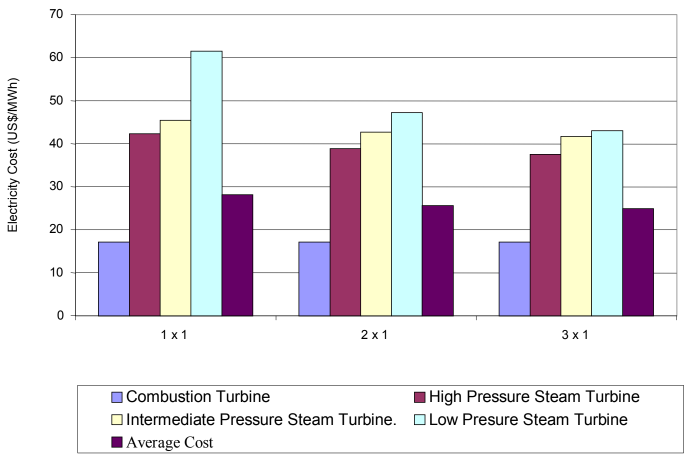

Figure 4. Electricity cost composition

By analyzing Table (2) it can be observed that the average cost was reduced by adding more combustion turbines. The installation costs also decreased, indicating a scale gain. Figure (4) depicts that the average costs is much influenced by the low pressure steam turbine in the 1x1 configuration. The other configurations show more equalized costs, however the electricity generation in this section is the highest considering all steam turbine sections. To solve this problem it is necessary either to decrease its production and its value or to increase production in other sections, in such a way that the average cost will be reduced. Table (3) presents results obtained during the optimization if a 2x1 ABB GT24 power plant.

Table 3: Cycle optimization

Study		1	2	3
Combustion Turbine power	MW	167,61	167,48	167,48
Plant Power	MW	490,12	505,81	512,01
Combustion turbine exergetic efficiency		0,35	0,36	0,36
Power Plant exergetic efficiency		0,52	0,54	0,55
High Pressure Steam Turbine Power	MW	49,28	41,15	41,15
Intermediate Pressure Steam Turbine Power	MW	44,98	60,91	60,95
Low Pressure Steam Turbine Power	MW	66,05	73,79	79,90
Installation Costs*	US$/kW	257,17	264,18	260,98
Electricity Cost – Combustion Turbine	US$/MWh	17,17	17,28	17,28
Electricity Cost – High Pressure Steam Turbine	US$/MWh	38,84	45,37	40,69
Electricity Cost – Intermediate Pressure Steam Turbine	US$/MWh	42,69	30,97	28,45
Electricity Cost – Low Pressure Steam Turbine	US$/MWh	47,22	45,73	36,01
Electricity average cost	US$/MWh	25,65	25,21	23,41

(*) Installation costs presented are referred to power island only (Gas Turbine World Handbook, 2005)

The first study shows results for the same configuration studied before. In study 2, reheat modules were added, along with other high and intermediate pressure modules. The efficiency increase can be observed, but the addition of a reheat section rearranged the steam and power generation inside, producing new results. The average cost was reduced; however, the low pressure section continues to push its value up. In study 3

Study 3 was obtained taking the condenser pressure to a lower value. As a result, the destruction of exergy in this equipment was reduced, which reduced also the exergy-based cost of the condensate and consequently of the boiler feed water. Hence, the steam was generated at a lower value, which pulled the costs down, especially in the low pressure section, which had its power production increased. The combined result, is, as in can be observed, a lower electricity average cost.

Figure (5) depicts the effect of the proposed law of variation over the exergy-based cost of the exhaust gases (see also Figure10). It can be observed that the stack exhaust carried no monetary value, and the cost is distributed to each module according to the exergy essence it captures. Hence the high pressure sections, which capture more of the exergy essence of the gas exhaust stream, received larger portion of costs.

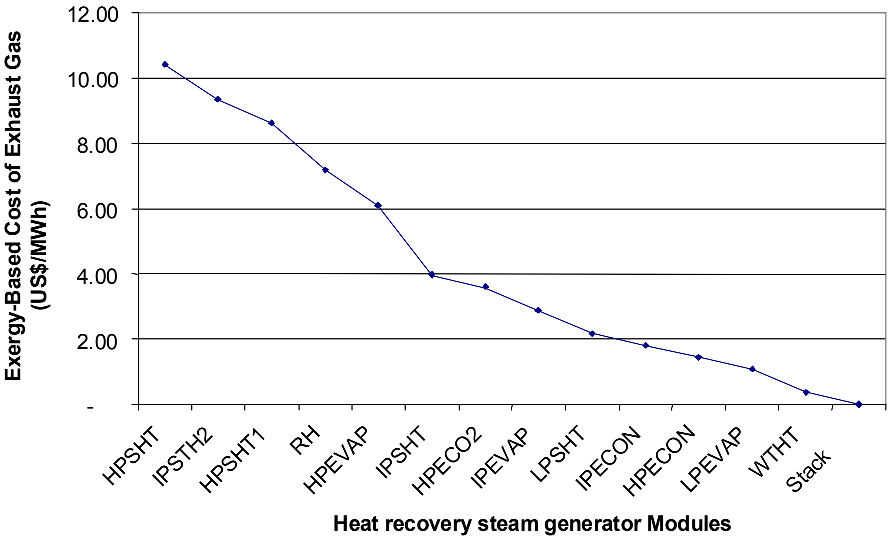

Figure 5. Effect of the Law of Variation

Aiming the demonstration of the applicability of the method to sensibility analysis, Figures (6) and (7) are presented below. Both based in a 1x1 SWPC 501FD power plant.

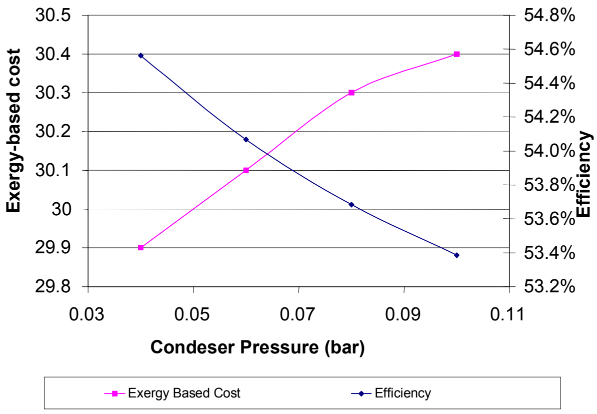

Figure 6. Sensibility Analysis: Condenser pressure

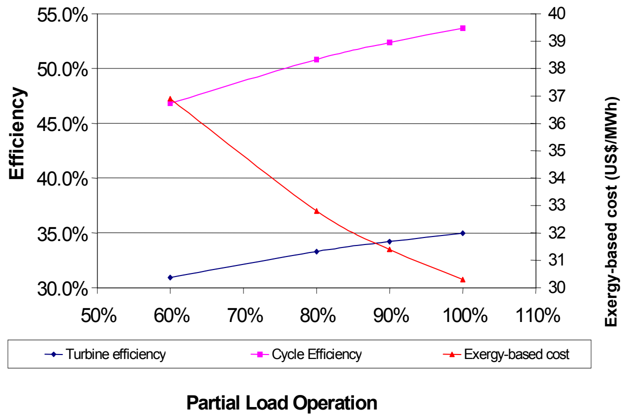

Figure 7. Sensibly Analysis: Partial Load Operation

Figure (6) depicts the response of the exergy-based cost and efficiency to a variation in the condenser pressure. As a lower condenser pressure implies in larger heat exchanger areas, pumps and cooling towers, the method allow the implatation costs to vary to capture these changes, and produce results also according to the heat balance modifications. Figure (7) depicts the behavior of the exergy-based cost according to the load condition of the power plant. Lower load conditions produce less efficient results, which can captured by the method when assigning cost according to exergy destruction, thus resulting in higher costs.

The last set of results comprises the study on supplementary firing. The base power plant model for this study is a 2x1 SPWC 501F, which generates 590 MW with using its full supplementary firing capacity, that corresponds to its design condition. The fuel burn in the heat recovery boilers is the decreased until it is completely turned off, in which case the power plant produces approximately 500MW. The installation cost is kept constant throughout the study in order to more accurately reflect the load variations and investment in excess capacity. Figures (8) and (9) depict the variation of the exergy-based cost of electricity and according both to power generation and to plant efficiency.

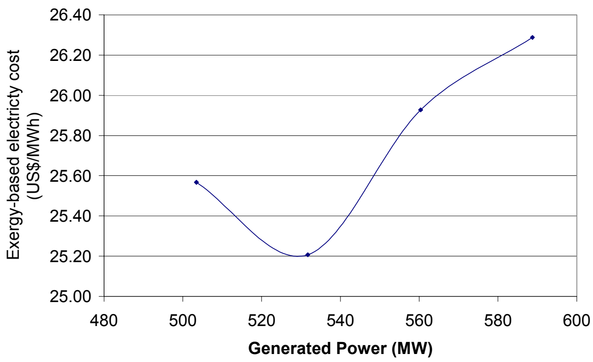

Figure 8. Cost variation according to Generated

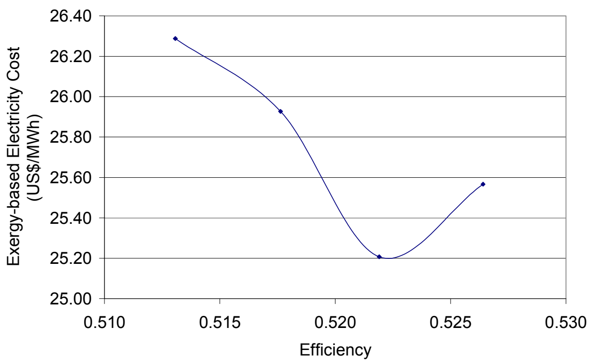

Figure 9. Cost Variation according to Efficiency

It can be observed that the efficiency decreases with the increase of power generation, which is to be expected since the supplementary firing causes this effect on the overall cycle efficiency. However, the exergy-based cost of electricity generated finds a local minimum value, which can be interpreted as the balance between the loss in terms of efficiency and its compensation in capital cost utilization, since operation the supplementary firing in less than 100% capacity implies in using less capacity than the installed.

4. Discussion

The proposed method proved itself capable of analyzing the composition of the electricity costs in a variety of combined cycle power plants configurations. The parametric cost estimation allows the method to vary implantation costs accordingly to the capacity of the equipments used, providing parameters for a cost x benefit analysis.

The application of thermoeconomic balances showed its benefits in terms of process analysis, allowing a detailed study of each stream that comprises the power plant. The proposed law of variation on the exergy-based cost of the exhaust gases contributed to identify the costs that contribute significantly to the composition of the electricity average cost.

Another benefit of the method is providing data for a cost x benefit analysis, combining thermoeconomics and parametric cost estimation. Investment decisions may be based on parameters provided by the method, in terms of equipment sizing and reheat application. As seen in the supplementary firing cases, similar analysis may provide data for peaking plant operation.

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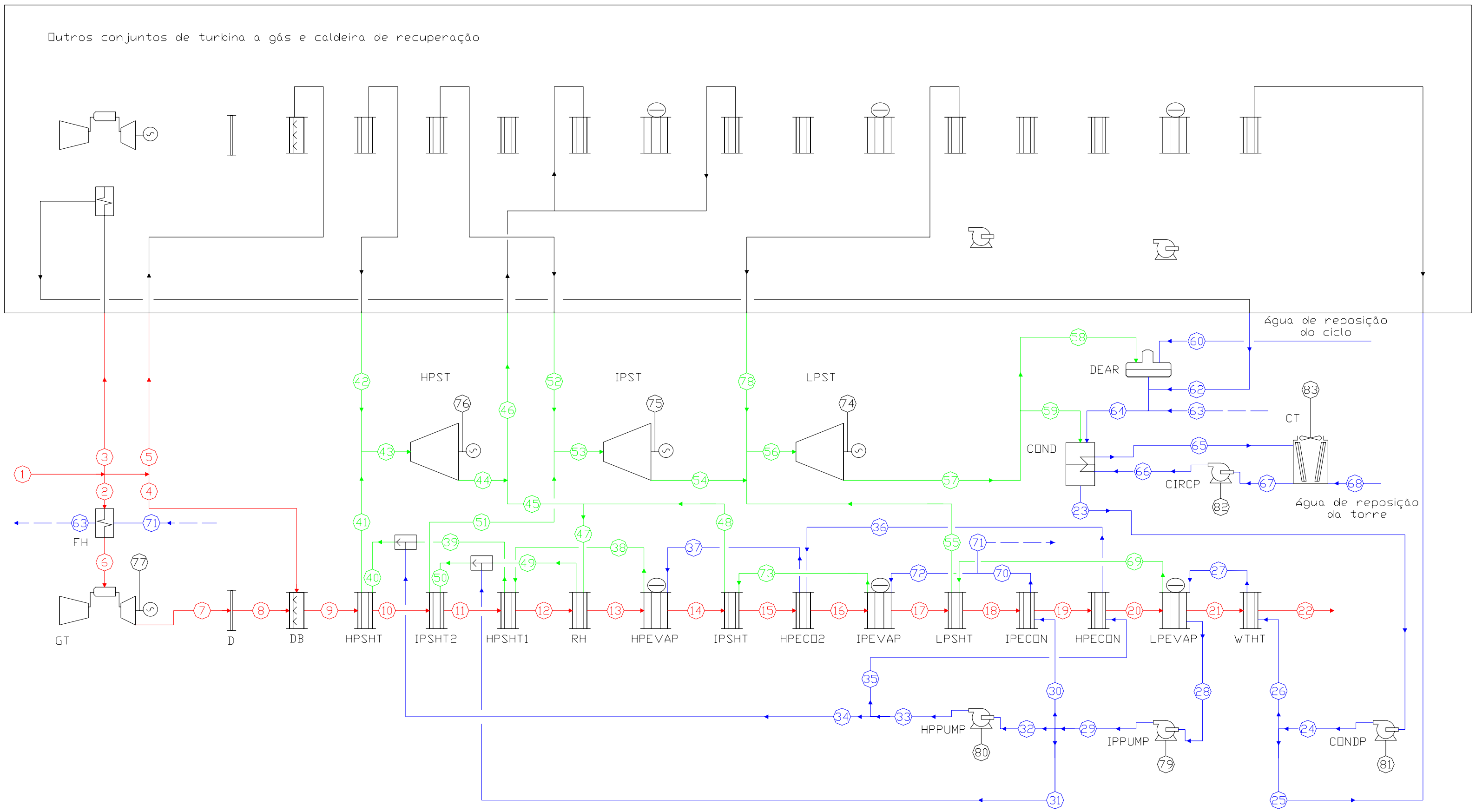

Figure 10. Power Plant Model