THERMOECONOMIC ANALYSIS AND OPTIMIZATION OF A THERMAL POWER PLANT: CASE STUDY- FIGUEIRA POWER PLANT

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Abstract. *This work presents the energetic, exergetic and thermoeconomic analyses and optimization of Figueira Power plant, located in center east of Paraná state, South of Brazil. The energetic analyses is made trough the application of the mass conservation principle and the fisrt principle of thermodynamics. The exergetic analyses, was executed including the second law of Thermodynamic, showing where exergy is destructed, giving a realist vision where end how the availability that enters the plant in the form of chemical exergy in the coal, is degraded in the components and what is the result over the whole plant, and over the cost of plant final product, electrical energy. The thermoeconomic analyses, was made following the mtethodology developed by professor George Tsatsarons, from Berlin Technical University (TU Berlin), where is calculated the cost balance for every component. This balance depends on the exergetic flows, which link these components. By the calculation of some parameter, which are the exergetic efficiency, the sum of the operation and maintenance costs plus the cost of exergy destruction, the relative cost difference, and the thermoeconomic factor, it is possible to make the thermeconomic evaluation of the components and the whole plant. The selection os new components was made using a thermoeconomic optimization approach, that is part of the adopted methodology and is based on the value of the total capital investiment for the components that the thermoeconomic evaluation pointed out as innefient. By using the same approach, the results are evaluted for the whole plant. The decisive parameter for decision making about the results attianed with the substiution of inneficient componets and improvement of the two Rankine cycles of the two power circuits of Figueira power plant, is the cost of the final power plant product, electrical energy.*

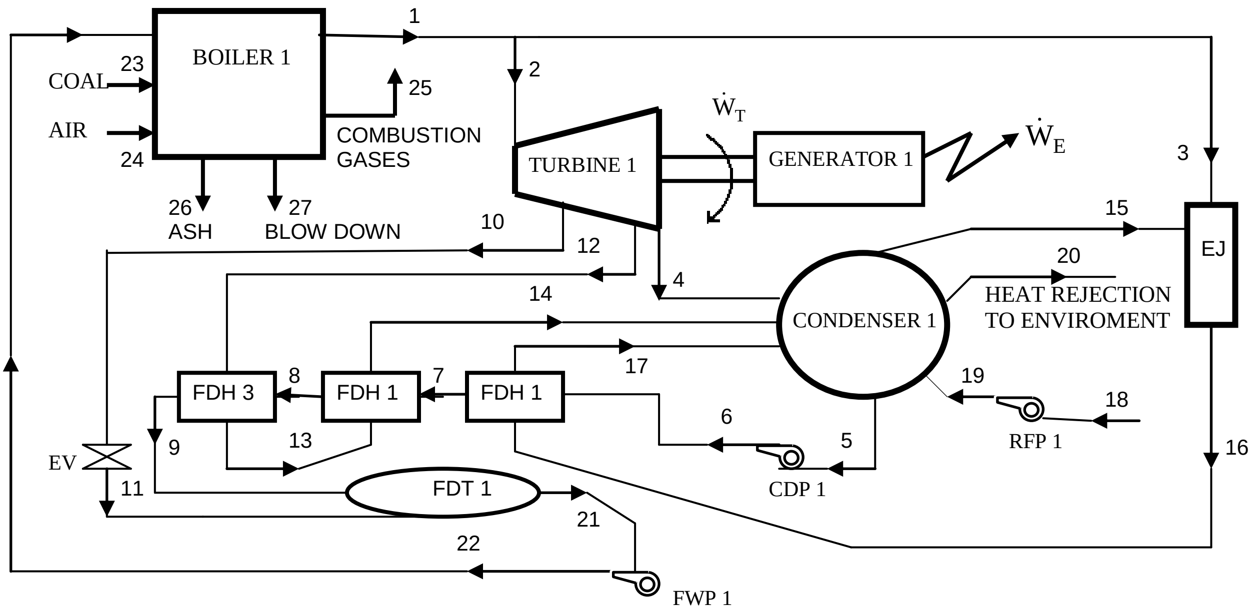
Keywords: *Power plant, thermoeconomic analysis, power plant thermoeconomic optimization.*

1. INTRODUCTION

Electrical energy generated in hydroelectric power plants is becoming rare in Brazil, needing to look for others trustable possibilities for generating energy in large scale. One of this possibilities, are steam power plants, Rankine thermodynamic cycle, using coal as fuel, because according to Lora et all (2004) there is coal for some hundred years of mankind use.

In Paraná State, at South Brazil, the Figueira thermal power plant is inside this possibility, being fed by mineral coal, from a mine next the site of the plant, having two power circuits using the Rankine thermodynamic cycle, with water as working fluid. Figures 1 and 2 below shows the power circuits 1 and 2 of Figueira power plant.

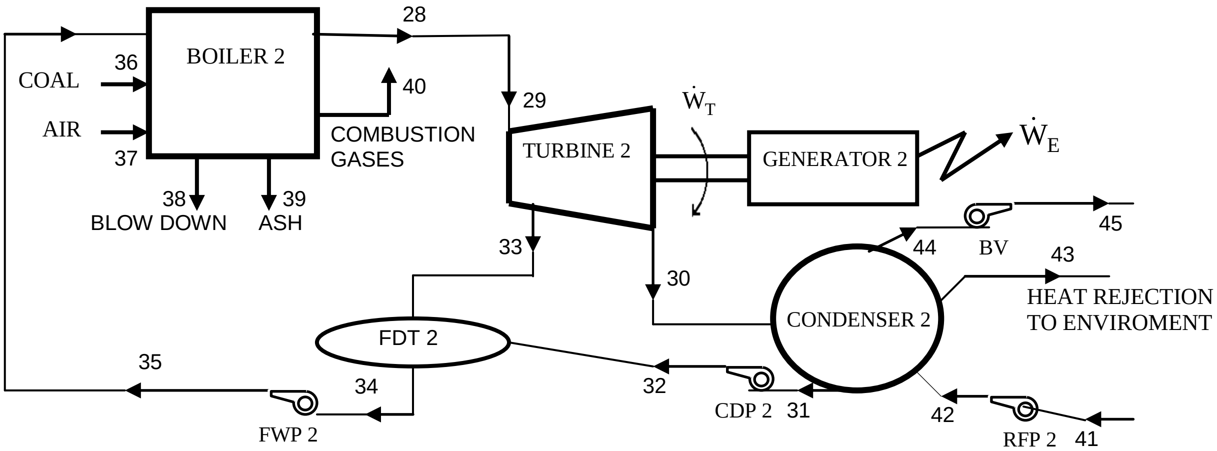
Figure 1. Functional scheme of power cycle 1 of Figueira power plant showing the main components.



Every component in figure 1 is a control volume where the boundary is the external wall of the component. Besides the components named explicitly, the legend for that using abbreviation in figure 1, is as follows:

CDP – Condensate pump; EJ – Ejector; EV – expansion valve; FDH – Feed water heater; FDT – Feed water tank FWP – Feed water pump; RFP – Refrigeration pump; $\dot{W}_T$ - Turbine power; $\dot{W}_E$ - Electrical energy; VP – Vacuum pump

Figure 2. Functional scheme of power cycle 2 of Figueira power plant showing the main components.



Every component in figure 2 is a control volume where the boundary is the external wall of the component. Besides the components named explicitly, the legend for that using abbreviation in figure 2, is the same specified above for figure 1.

2. TEORY

2.1. Energetic Analysis

The energetic analysis is developed applying the conservation of mass principle and the first principle of thermodynamics, for steady state working systems, and the equations are from Moran (2000):

Conservation of mass principle:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

$\dot{m}_i$ - Mass flow rate [kg/s]; *e* – Referred as “exit”; *i* – Referred as” inlet”.

First principle of thermodynamics:

$$\dot{Q}_{cv} + \dot{W}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e = 0 \tag{2}$$

$\dot{Q}_{cv}$ - Heat interactions between control volume (system) and environment [kW]; $\dot{W}_{vc}$ - Work interaction between control volume (system) and environment [kW]; h – Specific enthalpy [kJ/kg].

The data for application of Eq. (1) and (2), is shown in tab. 1, attained from Vieira (2002). The application of Eq. (1) and (2), in the components of the power circuits 1 and 2 of Figueira power plant, are showed in the tab. 2, below:

Table 1. Values of material flows in Figueira power circuits 1 and 2 measured at site.

Flow	$\dot{m}$ [kg/s]	t [C]	p [MPa]
1	10.0	435.0	3.818
2		425.0	3.57
3		424.0	3.72
4		51.0	
5		47.5	
6			0.9761

Table 2. Energetic functional parameters of Figueira power circuits calculated with Eq. (1) and (2).

Flow	$\dot{m}$ [kg/s]	t [C]	p [MPa]	h [kJ/kg]
1	10.0	435.0	3.818	3298.0
2	9.9802	424.0	3.72	3274.0
3	0.0198	425.0	3.57	3278.0
4	8.6223	51.0	0.01298	2445.0
5	9.028	47.5	0.0109	198.9
6	9.028	47.6	0.9761	200.29

Table 1. Values of material flows in Figueira power power circuits 1 and 2 measured at site (cont.).

Flow	$\dot{m}$ [kg/s]	t [C]	p [MPa]
7	9.028	54.32	
8		57.81	
9		80.01	0.4077
10		245.0	
11	0.972	234.0	0.2313
12		130.0	0.40
13			5.19
14	1.637	25.0	
15		25.0	0.1013
16	0.3		
17	0.425		0.1013
18		178.0	0.109
19		145.0	0.17
20		71.4	
21		56.0	
22		47.7	
23		120.1	
24		59.4	0.0213
25		27.0	0.1013
26		27.1	0.35
27		36.0	0.1013
28	9.528	432.0	3.818
29		422.0	3.72
30		62.0	
31		58.0	
32	8.028		0.9565
33	1.5		0.46
34		130.0	0.40
35			5.631
36	1.717	27.0	0.1013
37		27.0	0.1013
38	0.286		
39	0.446		0.1013
40		178.0	0.109
41		27.0	0.1013
42		27.1	0.35
43		37.0	0.1013
44	0.068	58.0	
45	0.068	58.2	0.1013

SOURCE: Vieira. 2002

Table 2. Energetic functional parameters of Figueira power circuits calculated with Eq. (1) and (2) (cont).

Flow	$\dot{m}$ [kg/s]	t [C]	p [MPa]	h [kJ/kg]
7	9.028	54.32	0.8624	227.7
8	9.028	57.81	0.6351	242.4
9	9.028	80.01	0.4077	335.7
10	0.972	245.0	0.55	2948.0
11	0.972	234.0	0.2313	2937.0
12	10.0	130.0	0.40	546.2
13	10.0	130.5	5.19	553.5
14	1.637	25	0.1013	52.0
15	12.77	25.0	0.1013	298.20
16	0.425	1290.0	0.1013	1525..2
17	0.3	251.8	0.1013	1087.0
18	14.11	178.0	0.1013	213.88
19	0.3859	145.0	0.17	2760.0
20	0.3859	71.4	0.03312	577.1
21	0.3859	56.0	0.0165	234.8
22	0.1	120.1	0.023	2724.0
23	0.1	59.4	0.0213	249.1
24	0.0802	47.5	0.0109	2587.0
25	510.62	27.0	0.1013	112.4
26	510.62	27.1	0.35	112.8
27	510.62	36.0	0.1013	150.29
28	9.528	432.0	3.818	3291.0
29	9.528	422.0	3.72	3270.0
30	8.028	62.0	0.02186	2425.0
31	8.028	58.0	0.01817	243.2
32	8.028	58.5	0.9565	244.6
33	1.5	197.0	0.46	2851
34	9.528	130.0	0.40	546.2
35	9.528	130.5	5.631	554.2
36	1.717	25.0	0.1013	52.0
37	13.39	25.0	0.1013	298.20
38	0.286	251.8	0.1013	1087.0
39	0.446	1290.0	0.1013	1345.2
40	14.81	178	0.1013	213.88
41	419.08	27.0	0.1013	112.4
42	419.08	27.1	0.35	112.8
43	419.08	37.0	0.1013	154.6
44	0.068	58.0	0.1817	243.2
45	0.068	58.2	0.1013	244.00

2.2. Exergetic analysis

Exergetic analysis is made applying the following equations, from Moran (2000):

Specific physical exergy:

$$e^{ph} = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) \tag{3}$$

e^{ph} – Specific physical exergy [kJ/kg]; u – Specific internal energy [kJ/kg]; p_0 – Atmospheric pressure at reference conditions [MPa]; v – Specific volume [m^3/kg]; v_0 - Specific volume at reference conditions [m^3/kg]; s – Specific entropy [kJ/kgK]; s_0 – Specific entropy at reference conditions [kJ/kgK]; T_0 – Reference temperature [K].

Specific flow exergy

$$e_f = h - h_0 - T_0(s - s_0) \tag{4}$$

e_f - specific flow exergy [kJ/kg]; h_0 – specific enthalpy at reference conditions [kJ/kg].

Interaction in the form of work:

$$\dot{E}_w = \dot{W} \tag{5}$$

$\dot{E}_w$ - Interaction of exergy work between system and environment [kW]; $\dot{W}$ - Work changed between system and environment [kW].

Interaction in the form of heat flow:

$$\dot{E}_Q = (1 - \frac{T_0}{T_j})\dot{Q}_j \tag{6}$$

$\dot{E}_Q$ - Interaction of exergy heat between system and environment [kW]; $\dot{Q}_j$ - environment [kW]; Tj – Surface system absolute temperature [K].

According to Bejan et al (1996) the chemical exergy of fuels, may be represented by its Higher Heating Value (HHV).
The ultimate analysis of the coal used in Figueira power plan, according to ASTM D3176, is showed in table 3 bellow:

According to Vieira (2002), the ultimate analysis of the coal used in Figueira power plant is as follows:
Carbon – 49.76 %; Hydrogen – 3.2 %; Oxygen - 7.78 %; Nitrogen -1.5 % ;Sulfur – 4.11 %; Water- 8.1 %; Ash – 25.97 %.
According to Vieira (2002), the chromatograph analysis of the combustion gases gives a concentration of 4.5 % of oxygen and 750 ppm of carbon monoxide, and the value of (HHV) to the coal used in Figueira. is 20642kJ/kg.
According to Bejan et al (1996), the molar chemical exergy of water is 45 kg/kmol, or 2.493 kJ/kg.
Applying Eq. (3) and (4) in the data from table 2, results in values of exergetic flows of matter in the 45 points of material flow in the power circuits of Figueira power plant showed in table3 below:

Table 3. Values of exergetic flows of matter in the power circuit 1 and 2 of Figueira power plant

Flow	s [kJ/kg K]	s_0 [kJ/kg K]	h [kJ/kg]	h_0 [kJ/kg]	e^{ph} [kJ/kg]	e^{ch} [kJ/kg]	e_f [kJ/kg]
1	6.911	0.3639	3298.0	103.9	1242.08	2.493	1244.58
2	6.889	0.3639	3274.0	103.9	1224.64	2.493	1227.13
3	6.913	0.3639	3278.0	103.9	1221.48	2.493	1223.98
4	7.596	0.3639	2445.0	103.9	184.85	2.493	187.34
5	0.6711	0.3639	198.9	103.9	3.41	2.493	5.903
6	0.6753	0.3639	200.29	103.9	3.56	2.493	6.053
7	0.7599	0.3639	227.7	103.9	5.73	2.493	8.226
8	0.8045	0.3639	242.4	103.9	7.14	2.493	9.628
9	1.077	0.3639	335.7	103.9	19.19	2.493	21.682
10	7.203	0.3639	2948.0	103.9	805.2	2.493	807.52
11	7.577	0.3639	2937.0	103.9	682.51	2.493	685.00
12	7.334	0.3639	2760.0	103.9	577.93	2.493	580.46
13	0.9738	0.3639	577.1	103.9	291.26	2.493	293.75
14	0.7814	0.3639	234.8	103.9	6.42	2.493	8.915
15	8.119	0.3639	2587.0	103.9	170.92	2.493	173.41
16	8.16	0.3639	2724.0	103.9	295.7	2.493	298.19
17	0.8247	0.3639	249.1	103.9	7.81	2.493	10.30
18	0.3922	0.3639	112.4	103.9	0.06226	2.493	2.555
19	0.3935	0.3639	112.8	103.9	0.04494	2.493	2.568
20	0.5161	0.3639	150.29	103.9	1.012	2.493	3.505
21	1.634	0.3639	546.2	103.9	63.62	2.493	66.11
22	1.652	0.3639	553.5	103.9	65.55	2.493	68.05
23	**	**	52.0	52.0	0.0	20642.0	20642.0
24	1.696	1.696	298.20	2 98.20	0.0	5.39	5.39
25	6.39	6.074	-2089.4	2370.5	155.89	140.12	296.01
26	*	*	1345.2	18.48	800.75	724.45	1525.2
27	3.097	0.3639	1087.0	103.9	168.23	2.493	170.72

Table 3. Values of exergetic flows of matter in the power circuit 1 and 2 of Figueira power plant (cont.)

Flow	s [kJ/kg K]	s_0 [kJ/kg K]	h [kJ/kg]	h_0 [kJ/kg]	e^{ph} [kJ/kg]	e^{ch} [kJ/kg]	e_f [kJ/kg]
28	6.901	0.3639	3291.0	103.9	1238.06	2.493	1240.56
29	6.882	0.3639	3270.0	103.9	1222.73	2.493	1225.22
30	7.316	0.3639	2425.0	103.9	248.33	2.493	250.82
31	0.8069	0.3639	243.2	103.9	7.22	2.493	9.71
32	0.8112	0.3639	244.6	103.9	7.35	2.493	9.83
33	7.087	0.3639	2951	103.9	842.61	2.493	845.10
34	0.3922	0.3639	112.4	103.9	0.06226	2.493	2.555
35	0.3935	0.3639	112.8	103.9	0.04494	2.493	2.568
36	0.5305	0.3639	154.6	103.9	1.028	2.493	3.52
37	1.634	0.3639	546.2	103.9	63.62	2.493	66.11
38	1.654	0.3639	554.2	103.9	65.72	23.80	68.21
39	**	**	52.0	52.0	-	20642.0	20642.0
40	1.696	1.696	298.20	298.20	0.0	5.39	5.39
41	6.43	6.041	-2089.4	2370.5	155.89	140.12	296.01
42	3.097	0.3639	1087.0	103.9	168.23	2.493	170.42
43	*	*	1345.2	18.48	800.75	724.45	1525.2
44	0.8069	0.3639	243.2	103.9	7.22	2.493	9.71
45	0.8082	0.3639	244.00	103.9	7.24	2.493	9.733

Applying Eq. (5) and (6) in the data of table 1, results in the values of exergtic flows of heat and work in the components of the power circuits showed in the figures 1 and 2. The results are showed in the tables 4 and 5 below, remembering that in figure 1 and 2, the boundary of every component, treated like a control volume at steady state. is the external wall of such component:

Table 4. Work and heat interaction flows in the components of the power circuit 1.

Component	$\dot{W}_k$ [kW]	$\dot{E}_Q$ [kW]
BOILER1	- 533.6	- 49.96
TUR 1	7655.00	0.0-
FDP 1	- 151.0	0.0
RFP 1	- 294.4	0.0
CDP 1	- 29.44	0.0
GEN 1	7402.0	- 23.85
COND 1	0.0	- 496.11
FDT 1	0.0	65.98
POWER CIRCUIT 1	6493.58	-17422.77

Table 5. Work and heat interaction flows in the components of the power circuit 2.

Component	$\dot{W}_k$ [kW]	$\dot{E}_Q$ [kW]
BOILER 2	- 533.6	52.4
TUR 2	7402.0	0.0
FP 2	-151.0	0.0
RF 2	- 257.6	0.0
CD 2	22.08	0.0
GEN 2	0.0	23.0
COND 2	0.0	398.96
FDT 2	0.0	184.78
POWER CIRCUIT 2	6274.28	17640.2

2.3. Thermoeconomics

According to Kreith (2000), thermoeconomics is the branch of engineering that combines exergetic analysis with economic principles, giving a true vision where energy is lost in the system, by exergy destruction and exergy loss to the environment.

The thermoeconomics analysis is a accountability of costs, where to generate a product the cost of the product must compensate the costs of the sum of fuel and the financial costs. Eq. (7), expresses this reasoning:

$$\dot{C}_{p,k} = \dot{C}_{f,k} + \dot{Z}_k^{AQ} + \dot{Z}_k^{O\&M} \tag{7}$$

p – Referred to "product"; f - Referred to "fuel"; $\dot{C}$ - Flow of costs [R$/s]; $\dot{Z}$ - Flow of costs of acquisition a maintenance and operation costs [R$/s].

The acquisition and operation and maintenance costs are joined and expressed by the following equation:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{O\&M} \tag{8}$$

To every exergetic flow of mass, work, and heat, may be associated a exergetic unit cost:
Mass flow:

$$\dot{C}_i = c_i \dot{E}_i = c_i (m_i \dot{e}_{f,i}) \tag{9}$$

$$\dot{C}_e = c_e \dot{E}_e = c_e (\dot{m}_e \dot{e}_{f,e}) \tag{10}$$

c - Exergetic unit cost [R$/kJ].

Flow of work:

$$\dot{C}_w = c_w \dot{E}_w \tag{11}$$

Flow of Heat:

$$\dot{C}_Q = c_Q \dot{E}_Q \tag{12}$$

Inserting the Eq. (9) to (12) in Eq. (7), results in the cost equation expressed in the form used for the cost balance in every component:

$$\sum_e \dot{C}_{e,\,k} + \dot{C}_{w,k} = \dot{C}_{Q,\,k} + \sum_i \dot{C}_{i,\,k} + \dot{Z}_k \tag{13}$$

Exergy destruction may be defined as the lost of exergy internally in the system by friction, finite temperature difference and mixing of fluids in different thermodynamic states and exergy loss is the exergy changed without useful, external to the system, generally given to the environment.

The calculation of the value of exergy destructed and the exergy lost is made, using the equations below, from Bejan et all (1996):

Exergy balance:

$$\sum (1 - \frac{T_0}{T_j}) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i e_{f,i} - \sum_e \dot{m}_e e_{f,e} - \dot{E}_d = 0 \tag{14}$$

$\dot{E}_d$ - Exergy destruction rate (inside the system) [kW].

Entropy balance:

$$\sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_g = 0 \tag{15}$$

$\dot{S}_g$ - Entropy generated internally in the system [kJ/kg k].

The entropy generated is calculated by the Gouy-Stodolola theorem. expressed by the following equation:

$$\dot{S}_g = T_0 \dot{E}_d \tag{16}$$

According to Kreith (2000), Eq. (14) may be expressed as follows and may be applied to a single component or to the whole power plant:

$$\dot{E}_{f,k} = \dot{E}_{p,k} + \dot{E}_{l,k} + \dot{E}_{d,k} \tag{17}$$

$\dot{E}$ - Flow of exergy in the form of fuel, product, internal system destruction or loss to the environment [kW];
k – Referred to component "k".

With Eq. (18) to (21), is possible to know the values of the exergy destruction and exergy loss in every component of the power circuits1 and 2 of Figueira power plant and in the whole plant.

To exergy destruction and exergy loss, may be associated a exergetic unit cost, that is calculated by the following equations:

$$c_{d,k} = \frac{\dot{C}_{d,k}}{\dot{E}_{d,k}} \tag{18}$$

$$c_{l,k} = \frac{\dot{C}_{l,k}}{\dot{E}_{l,k}} \tag{19}$$

2.4. The Methodology of Professor George Tsatsaronis

Professor Tsatsaronis methodology is based on the value of the thermoeconomic evaluation parameters. which equations are listed below:

Parameter	Symbol	Equation	
Exergy destruction rate:	$y_{d.k}$	$y_{d,k} = \frac{\dot{E}_{d,k}}{\dot{E}_{f,tot}}$	(20)
Exergy loosing rate:	$y_{l.k}$	$y_{l,k} = \frac{\dot{E}_{l,k}}{\dot{E}_{f,tot}}$	(21)
Exergetic efficiency:	ε	$\varepsilon_k = \frac{\dot{E}_{p.k}}{\dot{E}_{f,k}} = 1 - \frac{(\dot{E}_{d,k} + E_{l,k})}{E_{l,k}}$	(22)
Relative cost difference:	r_k	$r_k = \frac{1-\varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k^{CI} + \dot{Z}_k^{OM}}{c_{f,k}\dot{E}_{p,k}}$	(23)
Thermoeconomic factor:	f_k	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k}(\dot{E}_{d,k} + \dot{E}_{l,k})}$	(24)

In the methodology of professor Tsatsaronis, the criterions for thermoeconomic evaluation are:

1. List the components of the system in decreasing order of the sum $\dot{Z}_k + \dot{C}_{d,k}$;
2. Pay special attention to components that the sum of item 1 is high;
3. Pay special attention to components with high value of r_k;
4. If a component has a high value of r_k and a low value of f_k, the ε_k must be elevated. by investment of capital in the component;
5. If a component has a low ε_k and high values for $y_{d,k}$ and $y_{l,k}$. needs investment of capital to became more efficient;
6. If f_k is high. may be interesting to reduce the capital investment sacrificing the ε_k;
7. If f_k is low, it is interesting capital investment elevating the value of ε_k.

3. APPLICATION OF THE METODOLOGHY IN THE FIGUEIRA POWER PLANT

According to Horlock (2000), the costs of the materials and energetic (work and heat interactions) flows in a power plant for economical applications, must be levelized. and by using a Capital Recovery Factor applied to the period considered. The equation that takes in account the Capital Recovery Factor is as follows:

$$CRF = \frac{i(1+i)^n}{(1+ir)^n - 1} \tag{25}$$

CRF – Capital recovery factor; *ir* = Interest rate over the period (Period of 15 years. value of 4.5 % according to MME (2007). giving a CRF = 9.38 %)

The present levelized cost for the power circuits 1 and 2 of Figueira power plant are in tab. 6 and tab. 7 below:

Table 6. Levelized costs of power circuit 1 of Figueira power plant.

Component	$\dot{Z}_k$ [R$/S]
BOILER 1	0.046978
MSP 1	0.0000071
TUR 1	0.016474
GEN 1	0.002957
COND 1	0.0024524
CDP 1	0.000281
FWH 1	0.0001513
FWH 2	0.0002739
FWH 3	0.0004254
FWT 1	0.0006429
FWP 1	0.000649
RFP 1	0.0007933
EJ	0.0000071
TOTAL	0.072092

MSP - Main steam piping.

Table 7. Levelized costs of power circuit 2 of Figueira power plant.

Component	$\dot{Z}_k$ [R$/s]
BOILER 2	0.064519
MSP 2	0.00000948
TUR 2	0.020708
GEN 2	0.004026
COND 2	0.003548
CDP 2	0.0003836
FWT 2	0.0007673
FWP 2	0.0008632
RFP 2	0.001054
VP	0.0000013
TOTAL	0.09588

Appling Eq. (9) to (12). the present generation cost of power circuit one. is R$ 223.83/MWh and for power circuit 2 is R$ 255.89/MWh. Applying Eq. (2). (9). (14). (15). (18). (19) and (20) to (24), in every component of the power circuits 1 and 2 of Figueira power plant, are attained the values of the thermoeconomic evaluation parameters, which are in the tab 8 and 9 below:

Table 8. Exergetic and thermoeconomic evaluation parameter of power circuit 1 of Figueira power plant

Component	$\dot{E}_{l,k}$ [kW]	$\dot{W}_k$ [kW]	$\dot{E}_{d,k}$ [kW]	$c_{f,k}$ [R$/kJ]	$\dot{C}_{d,k}$ [R$/s]	$\dot{E}_{f,k}$ [kW]	$\dot{E}_{p,k}$ [kW]	ε_k [%]	$y_{d,k}$ [%]	$y_{l,k}$ [%]	r_k [%]	f_k [%]
BOILER 1	4277.9	-533.6	12471.4	1.2 E-05	0.1493	29048.26	11765.3	40.50	36.8	12.6	180.25	18.9
MSP 1	0.0	0.0	174.16	4.04 E-05	0.0071	12421.16	12247.0	98.60	0.51	0.0	1.42	0.1
TUR 1	0.0	7655.0	1967.8	4.04 E-05	0.0796	9622.84	7655.0	79.55	5.81	0.0	31.03	17.1
GEN 1	153.1	7501.9	0.0	5.30 E-05	0.00	7655	7501.9	98.0	0.0	0.45	2.78	31.0
COND 1	496.1	0.0	1066.1	4.04 -05	0.0565	1552.51	496.1	31.96	3.15	1.47	225.11	3.73
CDP 1	0.0	-29.44	28.095	1.15 E-03	0.039	29.44	1.354	4.6	0.08	0.0	2091.9	0.86
FWH 1	0.0	0.0	9.18	1.15 E-03	0.0103	28.79	19.61	68.11	0.03	0.0	47.49	1.4
FWH 2	0.0	0.0	97.26	8.74 E-04	0.085	109.92	12.66	11.52	0.29	0.0	770.53	0.32
FWH 3	0.0	0.0	1.82	8.01 E-04	0.0015	110.64	108.82	98.35	0.06	0.0	2.16	22.6
FWT 1	65.98	0.0	134.49	4.04 E-05	0.0055	861.57	661.1	76.73	0.40	0.19	32.73	7.4
FWP 1	0.0	150.88	13148	5.30E-05	0.007	150.88	19.4	12.85	0.39	0.0	741.31	0.09
RFP 1	0.0	294.40	162.66	5.30 E-05	0.0086	294.4	6.638	2.25	0.48	0.0	4569.9	8.42
EJ	0.0	0.0	8.32	4.04 E-05	0.0003	38.14	29.82	78.19	0.02	0.0	28.48	2.06
POWER CIRCUIT 1	4993.1	6493.6	16252.9	1.2 E-05	0.1946	27739.5	6493.58	23.4	48.0	14.8	419.93	22.1

Table 9. Exergetic and thermoeconomic evaluation parameter of power circuit 2 of Figueira power plant

Component	$\dot{E}_{l,k}$ [kW]	$\dot{W}_k$ [kW]	$\dot{E}_{d,k}$ [kW]	$c_{f,k}$ [R$/kJ]	$\dot{C}_{d,k}$ [R$/s]	$\dot{E}_{f,k}$ [kW]	$\dot{E}_{p,k}$ [kW]	ε_k [%]	$y_{d,k}$ [%]	$y_{l,k}$ [%]	r_k [%]	f_k [%]
BOILER 2	5165.2	- 533.6	12946.7	1.2 E-05	0.155	29815.67	11170.15	36.91	36.5	14.5	215.17	22.9
MSP 2	0.0	0.0	146.11	4.96 E-05	0.0073	11820.00	11673.90	98.76	0.41	0.0	0.0289	1.29
TUR 2	0.0	402.00	990.66	4.89E-05	0.0485	8392.66	7402.00	88.20	2.79	0.0	19.11	30.0
GEN 2	148.0	7253.9	0.0	5.83 E05	0.0000	7402	7253.96	98.00	0.0	0.42	2.99	31.8
COND 2	398.96	0.0	1536.01	4.89E-05	0.0752	1934.97	398.96	20.62	4.33	1.12	403.13	3.61
CDP 2	0.0	-22.08	21.12	1.24E-03	0.026	22.08	0.96	4.35	0.06	0.0	2231.2	1.45
FWT 2	184.78	0.0	531.89	4.89 E-05	0.0.26	1346.57	629.9	33.05	1.49	0.52	205.06	2.14
FWP 2	0.0	-150.88	131.0	2.55 E-04	0.0334	150.88	20.00	13.24	0.37	0.0	672.21	2.52
RFP 2	0.0	-257.60	255.45	5.83 E-05	0.0149	257.6	5.448	2.15	0.72	0.0	4883.0	6.61
VP	0.0	-14.72	14.06	4.89 E-05	0.0001	14.72	0.660	4.48	0.04	0.0	2136.2	0.19
POWER CIRCUIT 2	5896.9	62751	16573.0	1.2 E-05	0.1984	28745.04	6275.08	21.83	467	16.6	485.72	26.3

The costs of the electrical energy generated at present in Figueira power plant are very high. According to MME (2007), the competitive value of costs is about R$ 137.00/MWh. nowadays. The thermoeconomic analysis point out for the excessive exergy destruction and very high costs of operation and maintenance in the two boilers. Turbine 2 is also inefficient, almost 10 points in percentage less then turbine 1, destructing more exergy than what is acceptable. In the case of auxiliary equipment, like hopers and pumps, the impact of the costs of exergy destruction, exergy loss and the costs of operation and maintenance, is lower then the boilers and turbines. The condensers and the feed water tank will be maintained, because in such devices the aim is being done in a satisfactory manner.

4 – NEW CONFIGURATIONS FOR THE POWER CIRCUITS OF FIGUEIRA POWER PLANT

The choice for new components for the power circuits was made keeping in mind the original power of that power circuits, which was 10 MW. The procedure for optimization is based some equations, which are deducted and explained in detail in Bejan et all (1996) and are listed below:

Parameter	Symbol	Equation	
Total Capital Investiment:	TCI_k	$ITC_k = B_k\left(\dfrac{\varepsilon_k}{1-\varepsilon_k}\right)^{n_K}(\dot{E}_{p.k})^{m_K}$	(26)
Similarity thermoeconomic factor	F_k	$F_k = \dfrac{1}{1+\varepsilon_k^{OT}}$	(27)
Optimal exergetic efficiency:	ε_k^{OT}	$\varepsilon_K^{OT} = \dfrac{1}{1+F_K}$	(28)
Optimal operation and maintanace costs	$\dot{Z}_k^{OT}$	$\dot{Z}_k^{OT} = c_{f,k}\dot{E}_{p,k}\dfrac{F_k}{n_k}$	(29)
Optimal relative cost difference:	r_k^{OT}	$r_k^{OT} = \dfrac{n_k+1}{n_k}F_k$	(30)
Thermoeconomic factor:	f_k^{OT}	$f_k^{OT} = \dfrac{1}{1+n_k}$	(31)

B_k – Constant in TCI $_k$ equation [R/MW^m]; n_k - efficiency exponent; m_k - capacity exponent; $\dot{E}_{p,k}$ - Product [MW].

Trough Eq. (26) in levelized form, applied to the components, it is possible obtain the values B_k, n_k, and m_k, by numerical methods over the costs obtained in the market for that components. In Figueira power plant, the indication is changing the two boilers and turbine two. The costs of the boilers, with a scrubber and a high efficiency cyclone, and the turbine and the constant and exponents of Eq. (26) for these components are in tab. 10 below:

Table 10. Constant and exponents of Eq. (26), and product. exergetic efficiency and levelized total capital investment for new components in Figueira power plant. (Levelization period of 15 years)

Component	B_k [MW $^{-1}$]	n^k	m^k	$\dot{E}_{p,k}$ [MW]	ε_k [%]	TCI_k [R$]
TURBINE 1	16.622.2	1.5952	0.9001	10.0	87.35	3.600.000.00
TURBINE 2	16.622.2	1.5952	0.9001	10.1	88.21	4.100.000.00
BOILER	2.166.973	1.9992	0.9428	14.06	41.66	13.350.000.00

Using the same boiler of tab 10 in the two power circuits, and the present turbine in circuit 2 of Figueira power plant, the results obtained applying Eq. (26) to (31) are in tab 11 below:

Tabel 11. Values of the optimum and real thermoeconomic evaluation parameters, with the new components in the new configuration of the power circuits 1 and 2 of Figueira power plant.

New power circuit	$\dot{E}_{p,k}$ [MW]	F_k	ε_k^{OT} [%]	ε_k [%]	$\dot{Z}_k^{OT}$ [R$/s]	r_k^{OT} [%]	r_k [%]	f_k^{OT} [%]	f_k [%]	$c_{p,k}$ [R$/kJ]
1	10.0	1.29	43.8	24.0	0.166	161.2	349.3	51.9	12.1	3.426E-05
2	10.1	1.28	43.8	24.8	0.168	161.7	336.2	51.9	12.7	3.33 E-05

The costs of energy generation, $c_{p.k}$, in the new configurations, in the usual units, are R$ 120.28/MWh for power circuit 1 and R$ 123.34 for power circuit 2.

4. CONCLUSION

Figueira is nowadays an old and power plant. Observing the parameter, in the present power circuits the values of r_k and f_k, are higher then in the values of the same parameters in the new configurations, and what is decisive, the cost of the energy generate is almost a half of the present values. In the new configuration the environment is also protected, with the inclusion of modern equipments that ensure much less emissions to the environment. Finally, the total cost for the repowering is lower when compared with the installation a new power plant, which will be for 20 MW of net power, in present values, about R$ 68,0000,000.00 against about R$ 31,400,000.00 for the repowering, with two new trustable configurations, in spite of the use of old, but still very good components.

5. REFERENCES

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6. LITERATURE OF SIMILAR PAPERS

The papers below present similar analyses to that develop in the present work and are interesting reading for better understanding of this paper:

Silva, A. M. E., 2003, “Optimização numérica termo-económica de um sistema de cogeração”, Tese de Mestrado, Universidade de Minho (Portugal).

Vieira, L. S. R., Donatelli, J. L. M., Cruz, M. E. C., 2005, “Integration of a mathematical exergoeconomic optimization procedure with a process simulator: application to the CGAM system”, Engenharia Térmica, vol 4, N° 2, pp. 163 - 172.

7. RESPONSIBILITY NOTICE

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