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Abstract: In this paper, an exergy analysis is given as part of a comprehensive analysis that considers the proposed solution for adaptation of the conventional steam cycle in TPP Bitola to a combined gas cycle. The importance and significance of exergy analysis is defined. The parameters and components of the proposed plant are presented and put into an exergy analysis in appropriate mathematical model. The obtained results for the exergy losses in the system are presented.

Keywords: Exergy analysis, Combined gas cycle, Exergy losses.

1. Introduction

Energy analysis is not a sufficient approach for the evaluation of energy systems because the first law of thermodynamics does not recognize the true losses of useful energy. Exergy analysis predicts the thermodynamic performance and efficiency of components in energy systems and relies on the principles of the second law of thermodynamics through entropy change [1]. Exergy is defined as the maximum theoretically useful work obtained from the thermodynamic equilibrium between the system and the environment [2]. This analysis enables the detection of parameters with the possibility for improvement. For example, the efficiency of combined cycle gas plants reaches over 60% [3]. Many studies have been done that explain the change in system efficiency depending on water temperature, steam pressure, etc. [4]. Therefore, the "positive" energy losses from the proposed combined cycle gas plant are calculated here [5].

2. Brief description and parameters of the proposed CHP

The proposed solution includes a combined cycle in the block of TPP Bitola [5], where it is envisaged to have a gas cycle with two gas turbines (Table 1), two HRSGs (Table 2) and a steam cycle with one steam turbine (K-210- 130) which already exists in TPP Bitola (Table 3). A simplified scheme of the combined cycle is shown in Figure 1, [5].

Table 1. Input and output parameters of the gas cycle [5]

Parameter		Compressor				Combuster		Gas turbine			
		1		2			3			4	
		input		output	input	output	input	output			
Temperature	[°C]	t_1 (air)	20	t_2 (air)	478	t_3	1297	t_4	625		
Pressure	[bar]	p_1	1.013	p_2	17.73	p_3	17.73	p_4	1.013		
Mass flow	[kg/s]	m_a	538.44	m_a	538.44	m_g	550.44	m_g	550.44		
Enthalpy	[kJ/kg]	i_1	294.4	i_2	759.1	i_3	1724	i_4	930.8		
Entropy	[kJ/kg K]	s_1	5.771	s_2	5.827	s_3	6.678	s_4	6.845		

Table 2. HRSG parameters [5]

Parameter	Gases Input (4)	Gases Output (5)	Steam Input (g)	Steam Output (a)
Temperature [°C]	625	183	158	540
Pressure [bar]	1.013	1.013	6.8	130
Mass flow [kg/s]	m_g	550.44	m_s	194.4
Enthalpy [kJ/kg]	930.8	506.1	666.9	3445
Entropy [kJ/kgK]	6.845	6.125	1.923	6.577

Table 3. Parameters of the segments from a steam cycle in TPP Bitola [5]

Parameters	HP input (a)	HP output (b)	IP input (c)	IP output (d)	LP input (d)	LP output (e)	Condenser input (e)	Condenser output (f)	Deaerator input (f)	Deaerator output (g)
Temperature [°C]	540	340	540	180	180	38.8	38.8	38	38	158
Pressure [bar]	130	30.3	26.8	1.37	1.37	0.069	0.069	0.25	0.25	6.8
Mass flow [kg/s]	194.4	169.4	166.7	137.5	137.5	132.2	132.2	139.7	139.7	139.7
Enthalpy [kJ/kg]	3445	3094	3548	2834	2834	2458	2458	160	160	667

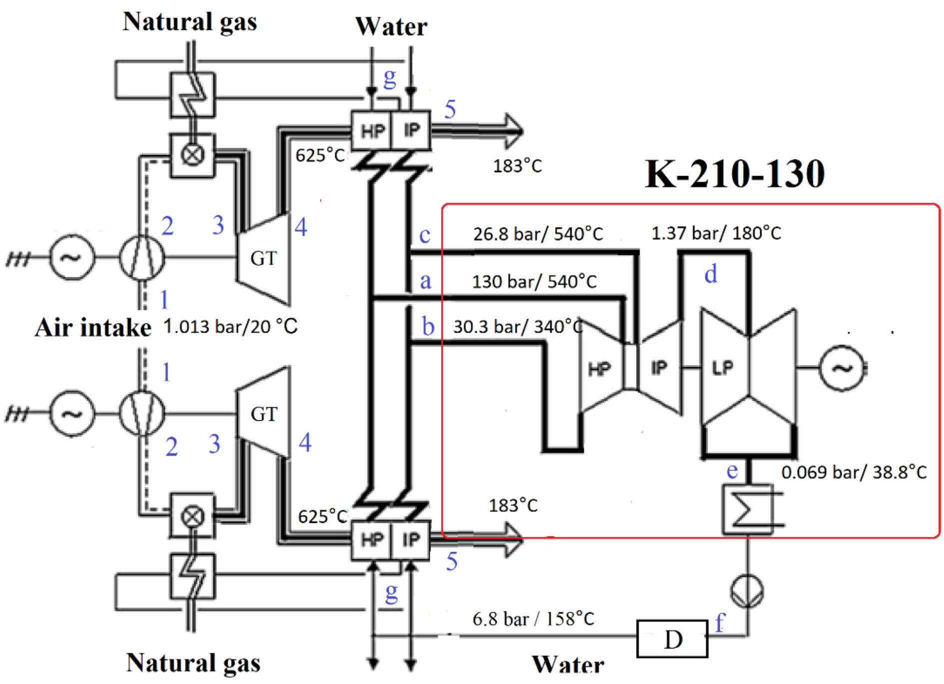

Figure 1. Conceptual solution for the combined cycle in TPP Bitola [5]

3. Exergetic analysis of the components

3.1. Compressor

Exergy of the air used in the compressor (E_c) is calculated as follows:

$$E_c = \dot{m}_a \cdot \left((i_2 - i_1) - T_1 \cdot (s_2 - s_1)\right) \quad (1)$$

where:

T_1 is an ambient temperature [K];

Exergy losses in the compressor are equal to:

$$I_c = W_c - \mathrm{E}_c \tag{2}$$

where:

W_c is a power of the compressor [MW];

The exergy efficiency of the compressor is:

$$\varepsilon_c = \frac{\mathrm{E}_c}{W_c} \tag{3}$$

The results for the compressor are shown in table 4.

Table 4. Exergy analysis of the compressor

Compressor	
W_c	251.47 MW
E_c	241.38 MW
I_c	10.09 MW
$\boldsymbol{\varepsilon_c}$	0.96 /

3.2. Combustion chamber

Exergy balance in combustion chamber is:

$$\mathrm{E}_f = E_3 - E_2 + I_{cc} \tag{4}$$

where:

E_f is the exergy of the fuel [MW];

E_2 is an exergy of inlet compressed air [MW];

E_3 is an exergy at the exhaust gases outle [MW];

I_{cc} are exeryc losses in the combustion chamber [MW].

Exergy of the incoming fuel (E_f) is expressed as:

$$E_f = m_f \cdot H_g \tag{5}$$

H_g is a high heating value of the fuel (natural gas), (H_g = 55.53 MJ/kg);

m_f is mass flow of the fuel, ($m_f = 12\ kg/s$); [5]

$E_3 - E_2$ is calculated as follows:

$$E_3 - E_2 = m_g \cdot \left((i_3 - i_2) - T_1 \cdot (s_3 - s_2)\right) \tag{6}$$

It follows that the exergy losses and the efficiency of the combustion chamber are:

$$I_{cc} = \mathrm{E}_f - (E_3 - E_2) \tag{7}$$

$$\varepsilon_{cc} = \frac{E_3 - E_2}{\mathrm{E}_f} \tag{8}$$

Table 5 shows the results for combustion chamber.

Table 5. Exergy analysis of the combustion chamber

Combustion chamber	
E_f	666.36 MW
E_3- E_2	393.87 MW
I_{cc}	272.5 MW

$\boldsymbol{\varepsilon_{cc}}$	0.591

3.3. Gas turbine

Exergy balance of the gas cycle is:

$$E_1 + E_f = E_4 + W_{GT} + I_{GT} \tag{9}$$

where:

E_1 is the exergy of the inlet air [MW];

E_4 is an exergy of the exhaust gases from the gas turbine [MW];

I_{GT} are the exergy losses from the gas cycle [MW];

W_{GT} is power of the gas turbine [MW].

E_{4-1} is calculated as:

$$E_{4-1} = \dot{m}_g \cdot \left((i_4 - i_1) - T_1 \cdot (s_4 - s_1)\right) \tag{10}$$

Exergy losses from gas cycle where $W_{GT} = 184.27$ MW are:

$$I_{GT} = E_f - (E_4 - E_1) - W_{GT} \tag{11}$$

The difference of the exergies corresponding to the net power of the gas cycle ($W_{GT} = W_t - W_c$) for each gas turbine is calculated by the expression:

$$(E_3 - E_4) - (E_2 - E_1) = \left[\dot{m}_g\left((i_3 - i_4) - T_1(s_3 - s_4)\right)\right] - [\dot{m}_a((i_2 - i_1) - T_1(s_2 - s_1)] \tag{12}$$

The efficiency of the gas turbine, ε_{GT}, (without losses from the combustion chamber) is:

$$\varepsilon_{GT} = \frac{W_{GT}}{E_{(3-4)} - E_{(2-1)}} \tag{13}$$

Friction losses in the gas turbine and compressor are:

$$I_{tr} = E_{(3-4)} - E_{(2-1)} - W_{GT} \tag{14}$$

The coefficient of net work of the whole gas cycle is:

$$\varepsilon = \frac{W_{GT}}{E_f} \tag{15}$$

Table 6 shows the results of the gas turbine and gas cycle.

Table 6 Exergy analysis of the gas turbine and gas cycle

Gas turbine and gas cycle	
W_{GT}	184.27 MW
E_f	666.36 MW
E_{4-1}	177.09 MW
$\mathbf{I_{GT}}$	305 MW
E_{3-4}-E_{2-1}	222.16 MW
$\boldsymbol{\varepsilon_{GT}}$	0.82 /
$\mathbf{I_{tr}}$	37.89 MW
$\boldsymbol{\varepsilon_{GT}}$	0.542 /

The calculated exergy losses are $I_{GT} = 305\ MW$, a value that includes the losses in the combustion chamber is $I_{cc} = 272.5$ MW, which means that the difference ($I_{GT} - I_{cc} = 32.5$ MW) represents the exergy losses of the other components of the cycle where do not include combustion chamber losses.

3.4. HRSG

In a HRSG, the heat from the exhaust gases leaving the gas turbine is used to increase the temperature of the supply water in the economizer, evaporator, and steam superheater. The exergy balance in HRSG is calculated by the expression:

$$\Delta E_g = \Delta E_W + I_{HRSG} \tag{16}$$

where:

ΔE_g is an exergy loss from the exhaust gases [MW];

ΔE_W is an exergy loss from the water [MW];

I_{HRSG} are exergy losses in HRSG [MW].

$$\Delta E_g = \dot{m}_g \cdot \left[c_p \cdot (T_4 - T_5) - T_1 \cdot (s_4 - s_5)\right] \tag{17}$$

$$\Delta E_w = \dot{m}_w \cdot \left[(i_s - i_f) - T_e \cdot (s_s - s_f)\right] \tag{18}$$

Therefore, HRSG losses and efficiency are calculated using the expressions:

$$I_{HRSG} = \Delta E_g - \Delta E_w \tag{19}$$

$$\varepsilon_{HRSG} = \frac{\Delta E_w}{\Delta E_g} \tag{20}$$

Results of the HRSG's analysis are shown in table 7.

Table 7. Exergy analysis of the HRSG

HRSG	
$\mathbf{\Delta E_g}$	154.46 MW
$\mathbf{\Delta E_W}$	137.5 MW
I_{HRSG}	16.94 MW
$\boldsymbol{\varepsilon}_{\mathbf{HRSG}}$	0.89

3.5. Steam turbine

The exergy balance for the steam turbine in TPP Bitola with its cylinders (HP, IP, LP) and steam extractions is generalized and calculated for each cylinder separately, including the losses (regeneration system, transport etc.) usually amounts to8% [6], while the other losses (condenser, generator, etc.) are included in lower calculations by the expression:

$$\Delta E_{ST} = W_{ST} + I_{ST} \tag{21}$$

$$\begin{aligned}\Delta E_{st} = 0.92 \cdot \{&\dot{m}_{s,HP} \cdot [(i_a - i_b) - T_1 \cdot (s_a - s_b)] + \dot{m}_{s,IP} \cdot [(i_c - i_d) - T_1 \cdot (s_c - s_d)] \\ &+ \dot{m}_{s,LP} \cdot [(i_d - i_e) - T_1 \cdot (s_d - s_e)]\}\end{aligned} \tag{22}$$

Exergy losses in the steam turbine are:

$$I_{ST} = \Delta E_{ST} - W_{ST} \tag{23}$$

Efficiency of the steam turbine is:

$$\varepsilon_{ST} = \frac{\Delta E_{ST}}{W_{ST}} \tag{24}$$

Table 8 shows the results of the steam turbine.

Table 8. Exergy analysis of the steam turbine

Steam turbine	
W_{ST}	224 MW
$\mathbf{\Delta E_{ST}}$	247.06 MW
I_{ST}	23.06 MW

ε_{ST}	0.907

4. Exergy balance of the combined cycle

The exergy from the fuel (natural gas) obtained from the two gas turbines is:

$$E_f = 2 \cdot \dot{m}_f \cdot H_g \tag{25}$$

The exergy used for the net power of the two gas turbines is 2· W_{GT}, while the total exergy losses of the gas cycle are:

$$\Delta E_{GT} = 2 \cdot I_{GT} \tag{26}$$

Exerget losses in both steam generators (HRSGs) are:

$$\Delta E_{HRSG} = 2 \cdot I_{HRSG} \tag{27}$$

The exergy used for the net power of the steam turbine is W_{ST},, while the total exergy losses from the steam cycle are I_{ST}.

The exergy losses of the exhaust gases from the two HRSGs are:

$$\Delta E_{iz} = 2 \cdot \dot{m}_g \cdot [(i_5 - i_1) - T_1 \cdot (s_5 - s_1)] \tag{28}$$

There are losses that are not included in the previous calculations, which refer to another system elements and the mathematical approximations:

$$E_{zag} = E_f - W_{GT} - \Delta E_{GT} - \Delta E_{HRSG} - W_{ST} - I_{ST} - \Delta E_{iz} \tag{29}$$

Overall review of the combined cycle is shown in Table 9 and Figure 2.

Table 9. Overall review of the exergy analysis in CC

	[MW]	[%]
exergy used to produced GT output power (x2)	368.54	27.67
exergy destruction in GT cycle (x2)	610	45.77
exergy destruction in HRSG (x2)	33.88	2.54
exergy used to produced ST output power (x1)	224	16.8
exergy destruction in ST cycle (x1)	23.06	1.73
exergy loss to the environment	66.03	4.95
unaccounted losses	7.26	0.54
fuel exergy (Σ)	1332.77	100

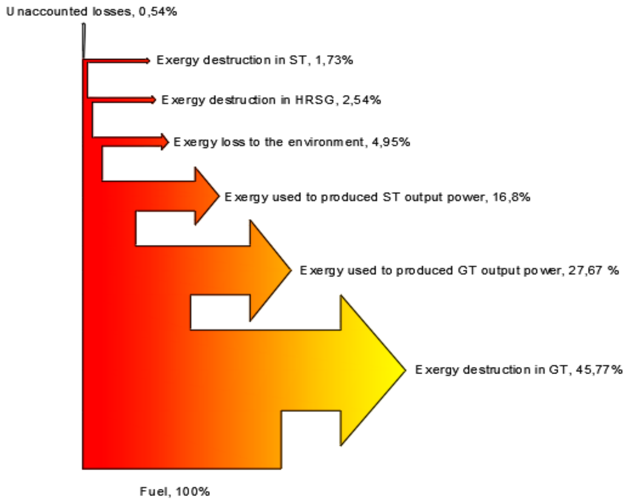

Figure 2 Exergy diagram in the GTCC

5. Conclusion

The analysis shows that exergetic efficiency (44.47%) is lower compared to energy efficiency (51.6%). The retention of the current steam cycle plant has a negative impact on the efficiency of the combined cycle compared to modern combined cycle plants because this solution excludes changes in the elements and parameters of the steam cycle, stacks, cooling towers etc.The proposed solution will contribute to the using of natural gas as a substitute for coal and will use the maximum potential of the existing steam turbine. The results are obtained according to the ambient temperature of 20℃ and the pressure of 1 bar. The higher degree of adaptation supported by more investments will further improve the efficiency of the combined cycle.

Nomenclature

HP	–	High pressure.
IP	–	Intermediate pressure.
LP	–	Low pressure.
CHP	–	Combined heat and power.
TPP	–	Thermal power plant.
HRSG	–	Heat recovery steam generator.
GTCC	–	Gas turbine combined cycle.

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