Exergoeconomic analysis of a combined heat and power system with the micro gas turbine (MGTCHP)

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This paper presents the results of exergy and exergoeconomic analyses applied to a combined heat and power system with micro-gas turbine (MGTCHP). Quantative balances of the exergy and exergy cost for each component and for the whole system are carefully considered, while exergy consumption and cost generation within the system are determined. The exergy analysis indicates that the exergetic efficiency of the MGTCHP system is 35.80% with 123 kW (as 99.15 kW-electrical power and 24.46 kW-hot water@363.15 K). On the other hand, the exergoeconomic analysis results show that the unit exergy cost of electrical power and hot water produced by the MGTCHP system are accounted as 26.808 €(GW)$^{-1}$ and 7.737 €(GW)$^{-1}$, respectively.

Keywords: micro-gas turbine, combined heat and power, cogeneration, exergy analysis, exergy efficiency, exergoeconomic analysis, exergy cost, unit exergy cost.

1. INTRODUCTION

Combined heat and power (CHP) system technologies are generally classified according to their prima movers. Currently available systems include steam turbines, gas turbines, combined cycle and reciprocating engines. There are also new technologies which are expected to become economically available in the next ten years. These include fuel cell, Stirling engine and micro-gas turbines (Cogen Europe, 2001; Colpan and Yesin, 2006). Micro-gas turbines available and in development are defined as gas turbines with electrical power capacity ranges between 30 and 350 kW. Micro-gas turbines just as large as gas turbines can be used in power generation and CHP applications. (Rosen and Dincer, 2005) Micro-gas turbines are able to operate on variety of fuels, including natural gas, sour gases and liquid fuels such as gasoline, kerosene and diesel fuel/distillate heating oil. Target customers on manufacturers include financial services, data processing centre, telecommunications, restaurants, lodging, retail office building and other commercial sector. In CHP applications, the waste heat from the turbine is used to produce hot water to heat building space, to

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drive absorption cooling or desiccant dehumidification equipment and to supply other thermal energy needs in a building or industrial process (US EPA, 2002). In spite of the efficiency of energy production in the CHP applications can be increased over 80% (Chang, 2001); the exergetic efficiency of more energy conversion systems at low levels due to irreversibility. Due to this, more meaningful efficiencies are evaluated through exergy analysis. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components. The exergoeconomic analysis method combines exergy analysis with economic analysis. The method provides a technique to evaluate the cost of inefficiencies or the costs of individual process streams, including intermediate and final products (Silveira and Tuna, 2003). The exergoeconomics is nowadays a powerful tool to study and optimize an energy system. The application field is the evaluation of utility cost as products or supplies of production plants, the energy cost between process and operations of an energy converter. Those costs are applicable in feasibility studies, in investment decisions, on comparing alternative techniques and operating conditions, in a cost-effective section of equipment during an installation, an exchange or expansion of an energy system. The main goals of this study are, (i) to derive the exergoeconomic balance of the MGTCHP system and its components, and (ii) to determine the cost of products and observe the cost formation within the system.

2. THE MGTCHP SYSTEM

2.1. General description:

A schematic of the MGTCHP system investigated is given in Figure 1. This system consists of an air compressor (*AC*), a combustion chamber (*CC*), a gas turbine (*GT*), a recuperator (*REC*), an electrical generator (*G*), a heat exchanger (*HE*), and a water pump (*WP*).

2.2. Assumptions:

In this study, the assumptions made are listed below:

(i) The MGTCHP system operates in a steady-state condition.
(ii) The ideal gas principles are applied to air and combustion gas.
(iii) The combustion reaction is complete.
(iv) The changes in the kinetic exergy and potential exergy are assumed to be negligible.
(v) The temperature and pressure of dead (environmental) state are 298.15 K and 101.325 kPa, respectively.
(vi) The exergetic analyses are made on the lower heating value (LHV) basis of natural gas. The natural gas compositions are given in Table 1.
(vii) The fixed parameters about the system are listed in Table 2.

2.3. Combustion balance:

For a 105.667 air/fuel mass ratio, the general combustion equation of this system is as follows;

Table 1. Natural gas composition

Component	Volume (%)a	Mass (%)	LHV ($kJkg^{-1}$)
CH_4	93.3401	88.832	50000
C_2H_6	0.2109	0.376	47525
C_3H_8	0.0290	0.100	46390
C_4H_{10}	0.0124	0.043	45775
N_2	6.4076	10.649	——-
Total	100.00	100	44661

Sources; Balli and Aras, (in press)

Table 2. Fixed parameters of the MGTCHP system

Item	Unit	Value
T_o	(K)	298.15
P_o	(kPa)	101
$\dot{W}_{WP}$	(kW)	0.85
$\dot{W}_G$	(kW)	100
R_{gas}	$(kJ(kgK)^{-1})$	0.292
R_{air}	$(kJ(kgK)^{-1})$	0.287
$^{*}CIC_{MGTCHP}$	(€)	156000
$^{*}TPEC_{MGTCHP}$	(€)	80000
i	(%)	10
j	(%)	12
n	(yr)	25
τ	(hr)	8200
Pr	$(YTL(kWhr)^{-1})$	0.042317
ER	$(YTL(€)^{-1})$	1.8521
$\dot{C}^{OM}$	$(€(yr)^{-1})$	9360

Sources; (WEC,2004)

$$0.9334CH_4 + 0.00211C_2H_6 + 0.00029C_3H_8 + 0.00012C_4H_{10} + 0.06408N_2 + 62.17335187(0.7448N_2 + 0.2059O_2 + 0.0003CO_2 + 0.019H_2O) \rightarrow 0.95764CO_2 + 3.305742H_2O + 10.92443O_2 + 48.49221N_2 \quad (1)$$

After combustion reaction, the mass compositions of combustion gases are obtained 2.33 % CO_2, 3.05 % H_2O, 19.36 % O_2, and 75.25 % N_2.

2.4. The specific heat capacity of air and combustion gas:

The specific heat capacity of the combustion gases is calculated from a composition of equations of each component in its mass percentage as follows (Moran and Shapiro, 1995),

$$c_{P,cg}(T) = 0.925749 + \frac{0.008477}{10^2}T + \frac{0.017307}{10^5}T^2 - \frac{0.07136}{10^9}T^3 \qquad (2)$$

The specific heat capacity of air is a function of temperature,

$$c_{P,air}(T) = 1.04841 - 0.000383719T + \frac{9.45378T^2}{10^7} - \frac{5.49031T^3}{10^{10}} + \frac{7.92981T^4}{10^{14}} \qquad (3)$$

Where the unit of temperature is Kelvin.

3. EXERGETIC ANALYSIS

Exergy analysis is a method that uses the conversion of mass and conservation of energy principles together with the second-law of thermodynamics for the analysis, design and improvement of energy systems. The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. The aim of the exergy analysis in this study is (i) to determine the exergy rate of each state illustrated in Fig.1, (ii) to calculate the input exergy rate, output exergy rate, exergy consumption rate, exergetic efficiency and fuel exergy depletion ratio of the components of the MGTCHP system.

3.1. General exergy terms:

In the absence of nuclear, magnetism, electricity and surface tension effects in the thermal systems, the total specific exergy for a flow of matter through a system can be expressed as;

$$\varepsilon = \varepsilon_{kn} + \varepsilon_{pt} + \varepsilon_{ph} + \varepsilon_{ch} \qquad (4)$$

Where the terms ε_{kn}, ε_{pt}, ε_{ph} and ε_{ch} denote the kinetic exergy, potential exergy, physical exergy and chemical exergy, respectively.

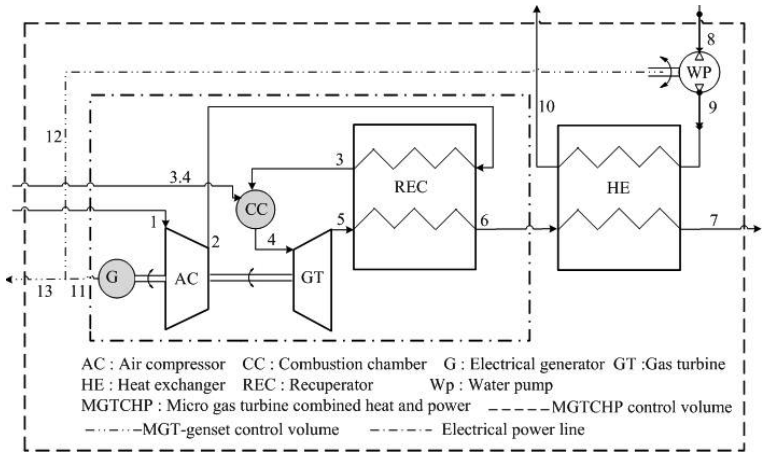


Figure 1. The schematic of the MGTCHP system investigated

The specific physical exergy for air and combustion gaseous with constant specific heat is obtained from literature (Kotas, 1995; Ebadi and Gorji-Bandpy, 2005).

$$\varepsilon_{ph} = c_{p(T)}\left[T - T_o - T_o \ln\left(\frac{T}{T_o}\right)\right] + RT_o\left(\frac{P}{P_o}\right) \tag{5}$$

The specific physical exergy of the steam is calculated by Moran and Sciubba, 1994

$$\varepsilon_{ph} = \left[(h - h_o) - T_o(s - s_o)\right] \tag{6}$$

An approximate formulation for the specific chemical exergy of gaseous hydrocarbon fuels as C_aH_b is given as (Moran, 1989),

$$\frac{\varepsilon_{ch}}{LHV} = \gamma_f \cong 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \tag{7}$$

Where γ_f denotes the fuel exergy grade function. γ_f is equal to 1.0308 for the natural gas composition given in Table 1.

The general exergy balance for steady-state flow system can be written as;

$$\sum\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k - \dot{W} + \sum_{in}\dot{m}_{in}\varepsilon_{in} - \sum_{out}\dot{m}_{out}\varepsilon_{out} - \dot{E}x_D = 0 \tag{8}$$

The term of $\dot{Q}_k$ represents the heat transfer rate through the boundary at temperature T_k at the location k, $\dot{W}$ is the work rate, $\dot{E}x_D$ is the exergy destruction rate.

3.2. Exergetic efficiency and fuel depletion ratio

The exergetic efficiency of the recuperator (REC) and heat exchanger (HE) are determined as follows (Wark, 1995)

$$\eta_{REC/HE} = \frac{\dot{E}x_{cold,out} - \dot{E}x_{cold,in}}{\dot{E}x_{hot,in} - \dot{E}x_{hot,out}} \tag{9}$$

The exergetic efficiencies of water pump (WP) are obtained from:

$$\eta_{WP} = \frac{\dot{E}x_{out,WP} - \dot{E}x_{in,WP}}{\dot{W}_{WP}} \tag{10}$$

The exergetic efficiency of the *i*'th component (excepting the REC, HE, and WP) of MGTCHP system are calculated by;

$$\eta_k = \frac{\dot{E}x_{out,k}}{\dot{E}x_{in,k}} \tag{11}$$

The exergetic efficiency of MGTCHP system is obtained from;

$$\eta_{MGTCHP} = \frac{\dot{E}x_{products}}{\dot{E}x^{ch}} = \frac{\left(\dot{W}_G - \dot{W}_{WP}\right)_{el} + \left(Ex_{out} - Ex_{in}\right)_{hotwater}}{\dot{E}x^{ch}} \tag{12}$$

The fuel exergy depletion ratio is written as the ratio of the exergy consumption of *i*'th component to the fuel exergy rate entering the MGTCHP system as follows;

$$\delta_i = \frac{\dot{E}x_{C,k}}{\dot{E}x^{ch}} \tag{13}$$

3.3. Results of Exergy Analysis:

The fluid type, temperature, pressure, mass flow rate, energy rate and exergy rate data for the MGTCHP system streams are given in Table 3 according to their state numbers as specified in Fig.1. After calculating exergy components of the states in Fig.1 and applying the exergy balances to subsystems of the MGTCHP system; the exergy consumption (destruction or/and loss), the exergetic efficiency and the fuel exergy depletion ratio are determined for each component and the whole MGTCHP system. The results of the exergetic analysis are illustrated in Table 4. The specific results of exergetic analysis of the MGTCHP system are given follow steps:

- The works of the air compressor (W_{AC}), gas turbine (W_{GT}) and electrical generator (W_G) are determined to be 149.34 kW, 256.51 kW and 100 kW, respectively.

- The electrical power of water pump is 0.85 kW. The net electrical power is 99.15 kW.
- The exergetic efficiency of the MGTCHP system is 35.80% with 123.61 kW (as 99.15 kW-net electrical powers and 24.46 kW-net hot water exergy rate). The total exergy consumption is 221.67 kW in this system.
- While the MGTCHP system is working in prime movers, it only produces 100 kW as electrical power and the exergetic efficiency of system is 29%.

Table 3.The energy rate, exergy rate and other properties at various system locations for one representative unit (for state numbers refer to fig.1 for the MGTCHP system).

State No.	Fluid type	Temperature $T(K)$	Pressure $P(kPa)$	Mass flow rate $\dot{m}(kgs^{-1})$	Energy rate $\dot{E}(kW)$	Exergy rate $\dot{E}x(kW)$
0	Air	298.150	101.325			
1	Air	298.150	101.325	0.793	0.000	0.000
2	Air	476.000	455.963	0.793	149.336	133.159
3	Air	908.970	446.843	0.793	549.524	341.662
3.4	Fuel	298.150	101.325	0.008	334.958	345.274
4	Combustion gas	1208.150	437.906	0.800	876.775	557.330
5	Combustion gas	971.660	105.419	0.800	620.266	287.036
6	Combustion gas	543.150	103.352	0.800	199.979	54.923
7	Combustion gas	363.150	101.325	0.800	44.028	4.840
0	Water	298.150	101.325			
8	Water	343.150	2250.000	1.850	351.500	27.889
9	Water	343.200	2500.000	1.850	352.240	28.354
10	Water	363.150	2450.000	1.850	506.900	52.345

Table 4.The exergy rate. exergetic efficiency and fuel depletion ratio parameters of the components of the MGTCHP system.

Component	$\dot{E}x_{in}$ (kW)	$\dot{E}x_{out}$ (kW)	$\dot{E}x_C$ (kW)	η $(\%)$	δ $(\%)$
Air compressor	149.34	133.16	16.18	89.17	4.69
Combustion Chamber	686.94	557.33	129.61	81.13	37.54
Gas turbine	557.33	543.55	13.78	97.53	3.99
Recuperator	232.11	208.50	23.61	89.83	6.84
Heat exchanger	50.08	23.99	26.09	47.90	7.56
Water pump	0.85	0.46	0.39	54.60	0.11
Generator mechanical shaft	102.04	100.00	2.04	98.00	0.59
GT mechanical shaft	256.51	251.38	5.13	98.00	1.49
Stack gas(7)			4.84		1.40
MGTCHP(overall)	345.27	123.61	221.67	35.80	64.20

4. ECONOMIC ASPECTS AND EXERGOECONOMIC ANALYSIS

4.1. Economic Aspects:

The aim of economic analysis in this study is to provide necessary inputs to be used in the exergoeconomic analysis. These inputs are the total purchased equipment cost (TPEC), the capital investment cost (CIC), the vested purchased equipment cost (VPEC), the levelized cost rates of capital investment cost, operating and maintenances cost, and fuel cost.

4.2. Total purchased equipment cost (TPEC):

The total purchased equipment (TPEC) cost includes the purchased equipment costs (PEC) of the micro-gas turbine generator set (MGT-genset) and heat exchanger (HE) and water pump (WP) of the MGTCHP system. Total purchased equipment cost (TPEC) is:

$$TPEC_{MGTCHP} = PEC_{MGT-genset} + PEC_{HE} + PEC_{WP} \tag{14}$$

4.3. Capital investment cost (CIC):

The capital investment cost consists of sum of the total purchased equipment cost (TPEC) and the other cost (OC) as building work, electrical works, gas works, plumbing works, and engineering etc.

$$CIC = TPEC_{MGTCHP} + OC \tag{15}$$

4.4. Vested purchased equipment cost (VPEC):

When reviewing the studies about the exergoeconomic analysis of thermal system in literature, generally the purchased equipment cost (PEC) was used for the levelized capital cost analysis. This method does not include the other costs as building work, electrical works, gas works, plumbing works, and engineering etc. For more reality cost analysis, the other cost flow must be taken in to the levelized capital investment cost. In this regard, we suggest using the vested purchased equipment cost (VPEC) values in the exergoeconomic analysis. The vested purchased equipment cost of k'th component of MGTCHP system is calculated as following:

$$VPEC_k = CIC\left(\frac{PEC_k}{TPEC_{MGTCHP}}\right) \tag{16}$$

4.5. Levelized cost method:

The algorithm of the hourly levelized cost method is composed of six steps. These are;

The present worth of the investigated system:

$$PW_{MGTCHP} = CIC_{MGTCHP} - S_{MGTCHP} PWF(i,n) \tag{17}$$

The salvage value:

$$S_{MGTCHP} = CIC_{MGTCHP}\, j \tag{18}$$

The present value factor (*PWF*):

$$PWF = \frac{1}{(1+i)^n} \tag{19}$$

Annual capital cost (*ACIC*):

$$ACIC_{MGTCHP} = P\dot{W}_{MGTCHP} CRF(i,n) \tag{20}$$

Capital recovery factor (*CRF*):

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \tag{21}$$

Annualized equipment cost of MGTCHP system:$\left(\dot{Z}^{T}_{MGTCHP}\right)$

$$\dot{Z}^{T}_{MGTCHP} = \frac{\phi ACIC_{MGTCHP}}{3600\tau} \tag{22}$$

Where ϕ is the factor of operating and maintenance cost and was taken as 1.06 in literature (Kwak et al, 2003). In this study, due to the operating and maintenance cost is calculated separately, ϕ is taken as 1.00. Eqn.(33) can be arranged as the hourly levelized capital investment cost of MGTCHP system component $\left(\dot{Z}^{CI}_{MGTCHP}\right)$ such as follows;

$$\dot{Z}^{CIC}_{MGTCHP} = \frac{ACIC_{MGTCHP}}{\tau} \tag{23}$$

Hourly levelized capital investment cost of k'th component $\left(\dot{Z}^{CIC}_{k}\right)$:

$$\dot{Z}^{CIC}_{k} = \dot{Z}^{CIC}_{MGTCHP}\left(\frac{VPEC_k}{CIC_{MGTCHP}}\right) \tag{24}$$

Where τ,*i*,*j* and *VPEC* are the total annual number hours of system operation at full load, the interest rate, the salvage value ratio, the life time of system and the vested purchased equipment cost .

The hourly operating and maintenance cost of kth component is obtained from the annual operating and maintenance cost of the MGTCHP system $\left(\dot{C}^{OM}_{MGTCHP}\right)$;

$$\dot{Z}^{OM}_{k} = \frac{\dot{C}^{OM}_{MGTCHP}}{\tau}\left(\frac{VPEC_k}{CIC_{MGTCHP}}\right) \tag{25}$$

The economical data of each component of the MGTCHP system is given in Table 5.

Table 5. The economical data and levelized cost rate associated with capital investment and O&M costs of the MGTCHP system

Component		*PEC* (€)	*VPEC* (€)	Z_k^{CIC} $(€(hr)^{-1})$	Z_k^{QM} $(€(hr)^{-1})$	Z_k^T $(€(hr)^{-1})$
MGTCHP						
	MGT-genset	74500	145275	1.930	1.063	2.993
	Heat exchanger	5000	9750	0.130	0.071	0.201
	Water pump	500	975	0.013	0.007	0.020
	Total	80000	156000	2.073	1.141	3.214
Other Cost						
	Building works	6500				
	Electrical works	7000				
	Gas works	6000				
	Plumbing works	17000				
	Measurement meters	6500				
	Financing. engineering. etc.	33000				
	Total OC	76000				
Capital investment cost (*CIC*)		156000				

The levelized fuel cost in the energetic terms $(\dot{FC}_e)$;

$$\dot{FC}_e = \frac{\Pr LHV\tau}{ER} \tag{26}$$

Where Pr, *LHV* and *ER* are the fuel sell price in the New Turkish Lira (YTL), the low heating value of natural gas, the exchange rate(YTL(€)$^{-1}$).

The hourly levelized fuel cost in the exergetic terms $(\dot{C}^f)$;

$$\dot{C}^f = \frac{\dot{FC}_e}{\tau}\left(\frac{LHV}{\varepsilon_f}\right) \tag{27}$$

4.6. Exergoeconomic aspects:

The aim of the the exergoeconomic analysis is to understand the cost formation process and calculate the cost rate of each product generated by the MGTCHP system. There are several methods for the exergy-costing of products in literature. The SPECO method is chosen to be used in this study. The specific exergy costing (SPECO) method proposed by Lazzaretto and Tsatsaronis, 1999, assigns a cost value to exergy

unit of each material and energy stream entering and leaving components so that the method yields many unknowns and consequently, requires auxiliary assumptions to estimate the production costs.

4.7. General cost balance equations:

The exergoeconomic analysis is a method which combines exergy analysis with economic analysis. Cost balance of a system may be written as following (Bejan et al, 1996)

$$\sum_{in} \dot{C}_k + \dot{Z}_k^T = \sum_{out} \dot{C}_k + \dot{C}_W \tag{28}$$

$$\dot{C}_k = c\dot{E}x_k \tag{29}$$

$$\dot{C}_W = c\dot{W} \tag{30}$$

$$\dot{Z}_k^T = \dot{Z}_k^{CIC} + \dot{Z}_k^{OM} \tag{31}$$

where $\dot{C}_k$ and $\dot{C}_W$ are the exergy costs of the streams and power; c is the unit exergy costs of stream and power; $\dot{E}x_k$ and $\dot{W}$ are the exergy of stream and power entering and leaving the control volume; $\dot{Z}_k^{CIC}$, $\dot{Z}_k^{OM}$ and $\dot{Z}_k^T$ are the hourly levelized costs of capital investment cost, operating and maintenance and the total levelized cost of equipment inside the control volume.

4.8. Exergoeconomic balance equations of the MGTCHP system and its components:

The exergoeconomic balance equations consist of the cost balance equation given in equation (28) and the auxiliary equations written according to the F (fuel) rule and P (product) rule. The F rule refers to the removal of exergy from an exergy stream within the component being considered, when for this stream, the exergy difference between inlet and outlet is considered in the definition of the fuel. The F rule states that the total cost associated with this removal of exergy must be equal to the cost at which the removed exergy was supplied to the same stream in the upstream components. The P rule refers to supply of exergy to an exergy stream within the component being considered. The P rule states that each exergy unit is supplied to any stream associated with the products at the same average cost. This cost is calculated from the cost balance and the equations obtained by applying the F rule (Lazzaretto and Tsatsaronis, 1999; Colpan and Yesin, 2006). The cost balance and auxiliary equations are given as follows

For the micro-gas turbine generator set (MGT-genset):

$$\dot{C}_1^a + \dot{C}_{3.4}^f + \dot{Z}_{MGT-genset}^T = \dot{C}_{11}^w + \dot{C}_6^{cg} \tag{32}$$

$$\dot{C}_1^a = 0 \qquad \text{Assumption} \qquad (33)$$

$$\frac{\dot{C}_{3.4}^f}{\dot{E}x_{3.4}} = \frac{\dot{C}_6^{cg}}{\dot{E}x_6} = \frac{\dot{C}_7^{cg}}{\dot{E}x_7} = c_f \qquad \text{F-rule} \qquad (34)$$

$$\frac{\dot{C}_{11}^w}{\dot{E}x_{11}} = \frac{\dot{C}_{12}^w}{\dot{E}x_{12}} = \frac{\dot{C}_{13}^w}{\dot{E}x_{13}} = c_w \qquad \text{P-rule} \qquad (35)$$

For the water pump (WP):

$$\left(\dot{C}_9^{hw} - \dot{C}_8^{hw}\right) = \dot{C}_{12}^w + \dot{Z}_{WP}^T \qquad (36)$$

$$\dot{C}_8^{hw} = 0 \qquad \text{Assumption} \qquad (37)$$

For the heat exchanger (HE):

$$\left(\dot{C}_6^{cg} - \dot{C}_7^{cg}\right) + + \dot{Z}_{HE}^T = \left(\dot{C}_{10}^{hw} - \dot{C}_9^{hw}\right) \qquad (38)$$

$$\frac{\dot{C}_{10}^{hw} - \dot{C}_9^{hw}}{\dot{E}x_{10} - \dot{E}x_9} = c_{hw} \qquad \text{P-rule} \qquad (39)$$

For whole micro-gas turbine combined and heat power system (MGTCHP):

$$\dot{C}_1^a + \dot{C}_{3.4}^f + \dot{C}_8^{hw} + \dot{Z}_{MGTCHP}^T = \dot{C}_{13}^w + \dot{C}_7^{cg} + \dot{C}_{10}^{hw} \qquad (40)$$

4.9. Other exergoeconomic parameters:

Bejan et al., 1996, suggested several exergoeconomic parameters to analyze the exergoeconomic performance and optimization of thermal system. The cost rate of exergy destruction, relative cost difference and exergoeconomic factor play a central role in the exergoeconomic analysis. The cost associated with the exergy destruction in a component or process is a hidden cost, but a very important one, that can be revealed only by an exergoeconomic analysis. Assuming that the product is fixed and that the unit cost of fuel of the kth component is independent of the exergy destruction, the cost of exergy destruction can be defined as follow,

$$\dot{C}_{D,k} = c_f \dot{E}x_{D,k} \qquad (41)$$

The relative cost difference is a useful variable for evaluating and optimizing a system component. The relative cost difference is

$$r_k = \frac{1-\eta_k}{\eta_k} + \frac{\dot{Z}_k^T}{c_f \dot{E}x_{product}} \qquad (42)$$

The exergoeconomic factor expresses as a ratio the contribution of the non-exergy related cost to the total cost increase. A low value of the exergoeconomic factor calculated for a major component suggests that cost savings in the entire system might be achieved by improving the component efficiency (reducing the exergy destruction and losses) even if the capital investment cost for this component will increase. On the other hand, a high value of this factor suggests a decrease in the investment costs of this component at the expense of the components efficiency. The exergoeconomic factor is defined for kth component by

$$\xi_k = \frac{\dot{Z}_k^T}{\dot{Z}_k^T + c_f\left(\dot{E}x_{D,k} + \dot{E}x_{L,k}\right)} = \frac{\dot{Z}_k^T}{\dot{Z}_k^T + c_f \dot{E}x_{C,k}} \tag{43}$$

4.10. Results of exergoeconomic Analysis:

The cost rate of products are found after solving the the cost balance and auxiliary equations given in the previous section. The cost formation in the MGTCHP system is given in Table 6. It can be observed that the highest cost rate is achieved as 9.651€ $(hr)^{-1}$ in electricity production at state no.11. The unit exergy cost of electricity and hot water products are 26.808€ GW^{-1} and 7.737€ GW^{-1}.

Table 6. Exergy flow rates, exergy cost rates and unit exergy costs of the MGTCHP system

State No.	$\dot{E}x$ $(GW(hr)^{-1})$	$\dot{C}$ $(€(hr)^{-1})$	c $(€(GW)^{-1})$
0	0.000	0.000	0.000
1	0.000	0.000	0.000
3.4	1.243	7.919	6.371
6	0.198	1.261	6.371
7	0.017	0.108	6.371
8	0.100	0.000	0.000
9	0.102	0.101	0.985
10	0.188	1.455	7.737
11	0.360	9.651	26.808
12	0.003	0.080	26.808
13	0.357	9.570	26.808

The values of the exergy destruction cost, relative cost difference and exergoeconomic factor of the MGTCHP system and its subsystems are calculated and given in Table 7. According to Table VII;

- The MGT-genset produces 100 kW-electric power and 54.923 kW-exhaust gas. The overall exergetic efficiency of the MGT-genset is 44.87%.

- Between the components of the MGTCHP system, the maximum exergy destruction cost and relative cost difference occurs in the MGT-genset. The exergoeconomic factor of the water pumps is 69.19% that is the highest value between the components.
- The exergy destruction cost, relative cost difference and exergoeconomic factor of the MGTCHP system are 5.084 €$(hr)^{-1}$, 54.925% and 38.733%, respectively.

Table 7. The exergy destruction cost rate, relative cost difference and exergoeconomic factor of the MGTCHP system and its subsystems

Components	$\dot{E}x_{in}$ $(GW(hr)^{-1})$	$\dot{E}x_{out}$ $(GW(hr)^{-1})$	$\dot{E}x_D$ $(GW(hr)^{-1})$	η $(\%)$	$\dot{C}$ $(€(hr)^{-1})$	r_k $(\%)$	ξ $(\%)$
MGT-genset	1.243	0.558	0.685	44.870	4.366	168.589	40.672
HE	0.180	0.086	0.094	47.902	0.598	27.831	25.131
WP	0.003	0.002	0.001	54.118	0.009	66.412	69.190
MGTCHP	1.243	0.445	0.798	35.801	5.084	54.925	38.733

5. DISCUSSIONS

In this study, the exergetic and exergoeconomic analysis of the MGTCHP system are made in a detail. The results of exergetic analysis showed that the largest exergy destruction is occurring in the combustion chamber, as expected, since the combustion reaction is an irreversible process. The exergy consumption (destruction + loss), the exergetic efficiency and the fuel depletion ratio of the MGTCHP system are 221.67 kW, 35.8% and 64.2%, respectively.

When reviewing the studies about the exergoeconomic analysis of thermal system in literature, generally the purchased equipment cost (PEC) was used for the levelized capital cost analysis. This method does not include the other cost rates as building work, electrical works, gas works, plumbing works, and engineering etc. For more reality cost analysis, the other cost flow must be taken in to the levelized capital investment cost. In this regard, we suggest using the vested purchased equipment cost (VPEC) values in the exergoeconomic analysis. The results of the exergoeconomic analysis showed that the unit exergy cost of electricity and hot water products are 26.808€GW^{-1} and 7.737€GW^{-1}. It is very interesting that the total capital investment cost $\dot{Z}^{CIC}_{MGT\text{-}genset}$ of the MGT-genset only influences the cost rate of the electricity output of the MGTCHP system. Between the components of the MGTCHP system, the maximum exergy destruction cost and relative cost difference occurs in the MGT-genset. For decreasing the unit exergy cost of the electricity production, the exergy destruction within the MGT-genset should be minimized.

The exergy destruction cost, relative cost difference and exergoeconomic factor of the MGTCHP system are calculated as 5.084€h^{-1}, 54.925% and 38.733%, respectively.

This study is not intended to find the optimum operating and economic conditions. Such conditions can only be found by applying the exergoeconomic optimization. Also, the exergoeconomic optimization will be carried out.

6. CONCLUSIONS

This paper points out the thermodynamic inefficiencies, cost formation and cast rate of products of the MGTCHP with the exergy terms. While WEB-sites of manufacturers show that the productions and applications of the MGTCHP system are increasing quickly. The manufacturers and users may maintain an opinion for future improvements of their system by checking the exergy destruction locations within the MGTCHP system. Additionally, the MGTCHP owners should know how much the products such as electricity and hot water cost. The results of this study can be gives a chance to chance the sale price of products and to review the system's economic policy. Additionally, the methodology and results of this paper can be beneficial in the analysis and design of the similar systems.

The results of the present study can be used as a basis for the exergoeconomic or thermoeconomic optimization.

NOMENCLATURE

$ACIC$	= annualized capital investment cost(€ yr^{-1})
c_p	= specific heat capacity ($kJkg^{-1}K^{-1}$)
$\dot{C}$	= cost rate(€ $(hr)^{-1}$)
CIC	= capital investment cost(€)
CRF	= capital recovery factor
$\dot{E}$	= energy rate (kW)
$\dot{E}x$	= exergy rate (kW)
ER	= Exchange rate ($YTL(€)^{-1}$)
FC_e	= energetic fuel price(€ hr^{-1})
h	= enthalpy ($kJkg^{-1}K^{-1}$)
hr	= hour
i	= interest rate(%)
j	= salvage value ratio(%)
LHV	= lower heating value of fuel ($kJkg^{-1}$)
n	= life time of system(yr)
$\dot{m}$	= mass flow rate (kgs^{-1})
OC	= other cost(€)
P	= pressure (kPa)
PEC	= purchased equipment cost(€)
Pr	= fuel price (€ $(kWhr)^{-1}$)
PW	= present worth(€)
PWF	= present worth factor
$\dot{Q}$	= heat transfer rate (kW)

r = relative cost difference(%)
R = universal gas constant ($kJkg^{-1}K^{-1}$)
s = specific entropy (($kJkg^{-1}K^{-1}$)
S = salvage value(€)
T = temperature (K)
$TPEC$ = total purchased equipment cost(€)
$\dot{W}$ = work rate or power (kW)
$\dot{Z}$ = hourly levelized cost rate(€hr^{-1})

Greek Letters
δ = fuel exergy depletion ratio (%)
ε = specific exergy rate ($kJkg^{-1}$)
γ = fuel exergy grade function (%)
η = exergetic efficiency (%)
τ = total annual number of hours of the system operation at full load(hr)
ξ = exergoeconomic factor(%)

Subscrips
a = number of carbon
AC = air compressor
b = number of hydrogen
C = exergy consumption
cg = combustion gas
ch = chemical
$cold$ = cold side
D = destroyed, destruction
f = fuel
G = generator
HE = heat exchanger
hot = hot side
k = k'th component
in = input
kn = kinetic
$MGTCHP$ = micro gas turbine combined and heat power
$MGT\text{-}genset$ = micro gas turbine generator set
out = output
p = constant pressure
ph = physical
pt = potential
REC = recuperator
WP = water pump

Superscripts
a = air

ch = chemical
cg = combustion gases
CIC = capital investment cost
hw = hot water
OM = operating and maintanence
T = total
w = work

Abbreviations
AC = air compressor
CC = combustion chamber
G = electrical generator
GT = gas turbine
HE = heat exchanger
MGTCHP = micro gas turbine combined heat and power
MGT-genset = micro gas turbine generator set
REC = recuperator
WP = water pump

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