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Exergoeconomic Analysis for Unit Gt14 of South Tripoli Gas Turbine Power Plant

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Abstract

Exergoeconomic (thermoeconomic) analysis is performed for the unit GT14 of South Tripoli (Libya) gas turbine power plant. The designed electrical power of the unit is 100MW (based on ISO conditions). The full operating load (electrical) is 85MW. The analysis is based on real time data and performed for three different loads; those are 85% (full operating load) 60%, and 40% of design load.

A systematic and general methodology for defining and calculating exergetic efficiencies, exergy destruction and exergy related costs in thermal systems is presented. The methodology is based on the Specific Exergy Costing approach. Results of exergy analysis show the exergetic efficiency increases from 20.54% at 40% design load to 29.12% at full operating load, and hence, the ratio of the total exergy destruction to fuel input exergy decreases from 61.03% at 40% design load to 48.63% at full operating load load, and the ratio of exergy loss with the exhaust gases to the input fuel exergy slightly increases from 18.43% to 22.25%. Results of exergoeconomic analysis show the average cost per unit exergy net power equal to 7.1$/GJ at 40% design load, and equal to 5.5$/GJ at 60% design load, and equal to 4$/GJ at full operating load . It is found that the cost of exergy destruction in the combustion chamber presents the main contribution to the total cost of exergy loss; its value varies in the combustion chamber from 1474$/h at 40% design load to 1123$/h at the full operating load. The contribution and the variation of cost of exergy destruction with load are lower for the other two main components.

Keywords: Exergy; Irreversibility; Exergoeconomic; Cost Formation; F-principle; P-principle.

Nomenclature

c	average cost per unit exergy ($/kJ)
s	entropy (kJ/kg.K)
$\dot{Z}$	equipment cost rate ($/h)
y	exergy destruction ratio
f	exergy economic factor
$\dot{I}$	irreversibility rate (kW)
x	mole fraction
PEC	purchase cost ($)
$\dot{C}$	stream cost rate ($/h)
T	tempearure (K)
Symbols	
ε	effectiveness
$\dot{\psi}$	exergy rate (kW)
ψ	specific exergy (kJ/kg)
Subscripts	
O	ambient
l	capital
CH	chemical
k	component "k"
D	destruction
F	fuel
L	loss
PH	physical
P	product
j	stream "j"
tot	total
Superscripts	
Cl	capital
OM	operating and maintenance

1. Introduction

Exergoeconomic (thermoeconomic) combines a detailed exergy analysis with appropriate cost balances to study and optimize the performance of energy systems from the cost viewpoint [1]. Essentially, there are two exergoeconomic techniques proposed in literature: the Exergoeconomic Functional Analysis (T.F.A.) and the Exergetic Cost Theory [2].

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The history of exergy analysis of thermodynamics and thermoeconomics, the performance evaluation of an energy system from the viewpoint of the second law of thermodynamics and thermoeconomics as well as applications of thermoeconmoic optimization techniques is reported [3].

A conventional vapor-compression desalting system is analyzed thermodynamically and economically by the concept of essergy and internal energy, where economic analysis using the concept of internal economy shows that the decomposition of the system into zones is not totally arbitrary [4].

The application of exergoeconomic analysis has found wide range of applications, for instance for designing and optimizing thermal energy storage units [5, 6], to evaluate the performance of multi stage flash thermal vapor compresssion desalination process [7], and for modeling of geothermal district heating systems for building applications [8].

Thermoeconomic Analysis of electricity production via SOFC with integrated allothermal biomass gasification is presented [9]. Among the different approaches in literature, Specific Exergy Costing (SPECO) [10] method is used in this work.

SPECO method for calculating exergy-related costs in thermal systems is presented [11], where general rules are formulated for defining fuel and product and for calculating the auxiliary costing equations (based on the F and P rules).

2. Gt14 of South Tripoli Power Plant

Exergoeconomic analysis by using the Specific Exergy Costing method (SPECO) [11] is performed to illustrate the power of using this kind of analysis in evaluating the performance of gas turbine power plants. Gas turbine unit GT14 of South Tripoli gas turbine power plant is selected to perform the analysis. The power plant was constructed by ABB a German-Swiss company in 1994 at Alswani city. The plant has a design total capacity of 500 MW distributed evenly among five units. This capacity constitutes more than one eight of the total installed capacity in Libya. The aim of the analysis is to investigate the cost formation process, and to evaluate the performance of unit GT14 from exergoeconomic point of view. Gas turbine unit GT14 consists mainly of three components; a combustion chamber, a compressor, and a turbine, as shown in Fig. 1.

The thermodynamic data, the exergy balance, the cost balance and auxiliary equations for the unit GT14 are found in tables 1, 2, and 3 respectively in the appendix.

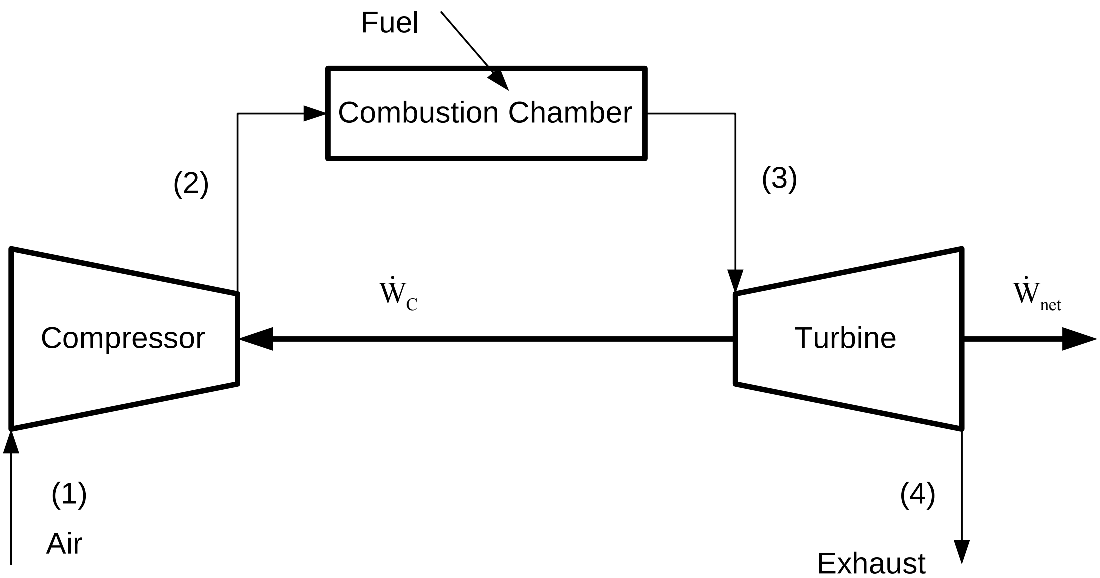

Figure 1. Schematic of the Unit GT14 of South Tripoli power station.

3. Assumptions

Fuel price (in Libyan dinar) is fixed and supported by the Libyan authorities; the current Libyan dinar is equal to 0.78 dollars at which the analysis is made. For the analysis the following assumptions are adopted:

1- Steady state and steady flow processes.
2- Ideal gas behavior for air and combustion products.
3- The fuel (light diesel) is modeled as n-Dodecane. The fuel is provided to the combustion chamber at the required pressure by a throttling process from a high-pressure source.
4- The combustion is complete, and N_2 is inert.
5- All components operate without heat loss (adiabatic).
6- The generator efficiency is 97%.

Power plant productivity is controlled according to the demand of electrical energy by controlling of the amount of fuel, which enters to the combustion chamber.

4. Exergoeconomic Analysis

Exergy can be found as [12]:

Physical Exergy:

$$\psi_{PH} = (h - h_O) - T_O(s - s_O) \quad (1)$$

Chemical Exergy:

$$\psi_{CH} = \bar{R}\,T_0 \sum x_i \ln\left(\frac{x_i}{x_0}\right) \quad (2)$$

Exergy Balance:

$$\sum \dot{\Psi}_{in,k} = \sum \dot{\Psi}_{out,k} + \dot{\Psi}_{L,k} + \dot{I}_{D,k} \quad (3)$$

Effectiveness:

$$\varepsilon = \frac{\text{outlet exergies}}{\text{inlet exergies}} \quad (4)$$

5. The Auxiliary Equation Rules

The following two rules for formulating the auxiliary equations are valid, when finding the specific costs of exergy associated with flows is desired [11]:

5.1. F-Principle:

The total cost associated with the removal of exergy must be equal to the cost at which the removed exergy was supplied to the same stream in upstream components.

5.2. P-Principle:

Each exergy unit is supplied to any stream associated with the product at the same average cost.

6. Cost Balance

Exergy costing usually involves cost balances formulated for each system component separately. A cost balance applied to the *k*-th component shows that the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the appropriate charges due to capital investment ($\dot{Z}_k^{CI}$) and operating and maintenance expenses ($\dot{Z}_k^{OM}$). The sum of the last two terms is denoted by $\dot{Z}_k$ [11]:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (5)$$

The steady-state form of control volume cost balance is

$$\sum_{j=1}^{n} \dot{C}_{j,k,out} = \sum_{j=1}^{m} \dot{C}_{j,k,in} + \dot{Z}_k \quad (6)$$

Some auxiliary equations expressed explicitly or implicitly. These auxiliary equations depend on the purpose of the component within the overall system, which is expressed by the exergetic efficiency:

$$\varepsilon_k = \frac{\Psi_{P,k}}{\Psi_{F,k}} \quad (7)$$

An important characteristic of exergoeconomic is the definition of exergy related specific costs.

$$c = \frac{\dot{C}}{\dot{\Psi}} \quad (8)$$

7. Exergoeconomic Variables

The exergoeconomic evaluation is conducted at the component level with the aid of a series of exergoeconomic variables. The rate of exergy destruction is calculated with the aid of an exergy balance, which, after introduction of fuel and product, may be written as [12]:

$$\dot{I}_{D,k} = \dot{\Psi}_{F,k} - \dot{\Psi}_{P,k} - \dot{\Psi}_{L,k} \quad (9)$$

The exergy destruction ratio relates the exergy destruction in the *k*-th component to the input fuel of the overall plant [11]:

$$y_{D,k} = \frac{\dot{I}_{D,k}}{\dot{\Psi}_{Fuel}} \quad (10)$$

The cost rates $\dot{C}_{F,k}$ and $\dot{C}_{P,k}$ associated with the fuel and product, respectively, are formed in the same way as the exergy rates $\dot{\Psi}_{F,k}$ and $\dot{\Psi}_{P,k}$ associated with fuel and product. Then the average costs per unit of fuel exergy ($c_{F,k}$) and product exergy ($c_{P,k}$) are calculated from [10]:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{\Psi}_{F,k}} \quad (11\text{-a})$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{\Psi}_{P,K}} \quad (11\text{-b})$$

The cost rate associated with exergy destruction is estimated as follows:

$$\dot{C}_{D,k} = c_{F,k}\dot{I}_{D,k} \quad (12)$$

The cost balance can now be written as:

$$\sum c_{P,k}\dot{\Psi}_{P,k} = \sum c_{F,k}\dot{\Psi}_{F,k} + \dot{Z}_k \quad (13)$$

One indicator of exergoeconomic performance is the exergoeconomic factor, *f*. The exergoeconomic factor is defined as [11]:

$$f_k = \left(\frac{\dot{Z}_k}{c_{F,k}\dot{I}_{D,k} + \dot{Z}_k}\right) \quad (14\text{-a})$$

Or,

$$f_k = \left(\frac{1}{\frac{c_{F,k}\dot{I}_{D,k}}{\dot{Z}_k} + 1}\right) \quad (14\text{-b})$$

The exergoeconomic factor for a component indicates the ratio between the price of the component and the cost of exergy destruction by the component. A low value of *f* indicates a component with low initial cost and high exergy destruction cost. More money could be spent on a component with low *f* to improve the overall cost effectiveness of the system. On the other hand, a component with high *f* has very high component costs and low exergy destruction costs. Less money should be spent up front on a low-*f* component to improve cost effectiveness of the system. The exergoeconomic factor can be calculated for each of the components in the system. The range of this indicator is between 0 and 1: If f is close to 0, the cost of irreversibilities is predominant (high value of 1, which is the sum of the irreversibilities and the exergy losses related to residue flows); when f is close to 1, the capital cost has greater influence. Generally, in plants running on fossil fuels, a good compromise is reached when intermediate values occur [11] with the product for the overall system is given by:

$$\dot{C}_{P,tot} = \dot{C}_{net} + \dot{C}_4 \quad (15\text{-a})$$

$$\dot{C}_{P,tot} = \dot{C}_1 + \dot{C}_f + \sum_k \dot{Z}_k \quad (15\text{-b})$$

8. Economic data

Taking the operating cost equals to fuel and maintenance costs per year, and are given as 8418256$ and 421230$ respectively. Total number of hours of system operation per year is 8449 hours. The cost rate of fuel is786$/h, 926$/h and 1153$/h at 40%, 60% and 85% design load respectively. Table (1) shows the economic data for the unit GT14 (values labeled with * are not available for the unit and typical values are taken from the literature, and are very close to real values).

9. Results and Discussion

The Excel Software is utilized to perform exergy and exergoeconomic analysis. The rate of exergy flow together with the input fuel exergy, compressor work, turbine work, and net power equal to 41 MW (40% design load), 62 MW (60% design load), and at 85MW (full operating load) are shown in Fig. 2. Better performance is obtained as the full operating load being approached, the analysis shows that the fuel exergy increases from 200.75MW at 40% design load to 301.06MW at full operating load, accordingly the exergy of the product of combustion at turbine inlet increases from 231MW to 305MW, and hence, turbine output increases from 37MW to 67MW. Since the unit runs more efficient at the full operating load, the compressor work decreases from 142.4MW at 40% design load to 140.15MW at full operating load, where the exergy of air leaving the compressor is kept a constant.

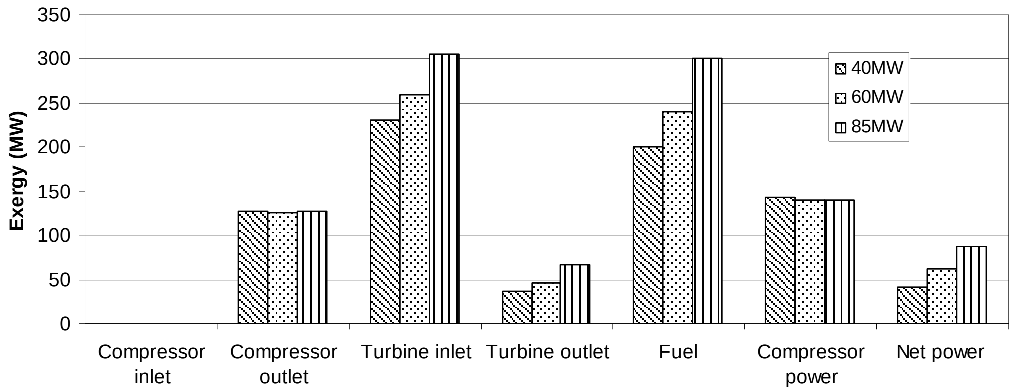

Fig. 2. Exergy flow rate at different loads.

Essentially, gas turbine power plants suffer from their low efficiency when compared with steam power plants. Fig. 3 shows that the exergetic efficiency increases from 20.54% at 40% design load to 29.12% at full operating load, and hence, the ratio of the total exergy destruction to fuel input exergy decreases from 61.03% at 40% design load to 48.63% at full operating load. Although Fig. 2 shows that exergy of the exhaust at the turbine outlet increases from 39.4MW at 40% design load to 61.8MW at full operating load, it is found, as shown in Fig. 3, that the ratio of exergy loss with the exhaust gases to the input fuel exergy slightly increases from 18.43% to 22.25%, that mean, the performance of gas turbine power plants can be further enhanced by recovering the exergy of the exhaust gases.

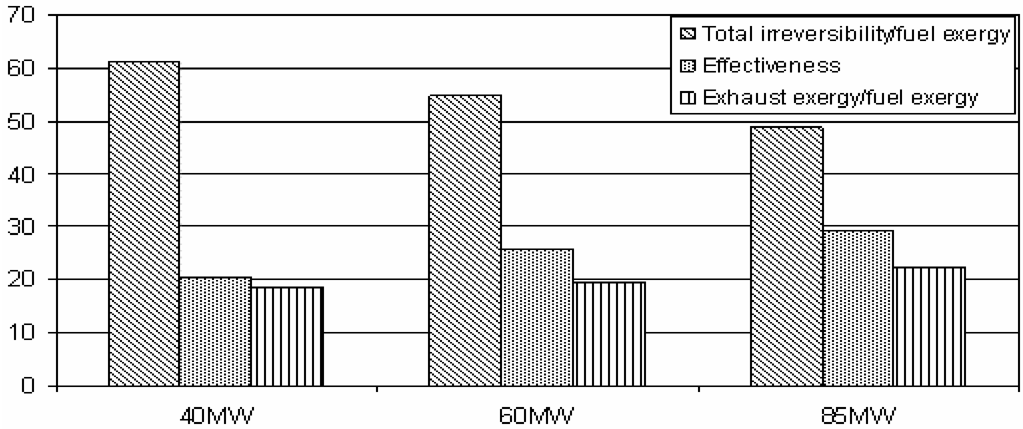

Figure 3. The Exergetic efficiency, the ratio of total Exergy destruction and the ratio of turbine outlet exergy relates the exergy fuel for the unit GT14, at different loads.

The rate of exergy destruction for the three main components is shown in Fig. 4. As expected, the exergy destruction in the combustion chamber presents the main contribution to the total exergy destruction; its value varies from 97.28MW at 40% design load to 122.64MW at the full operating load. The contribution and the variation of exergy destruction with load are minor for the other two main components.

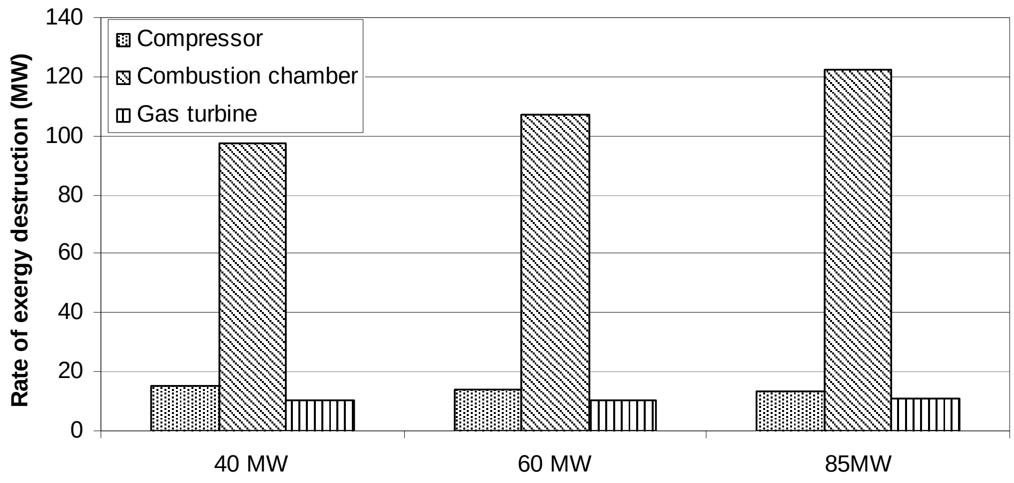

Figure 4. The rate of exergy destruction, at different loads.

Although, the rate of exergy destruction in the combustion chamber increases with the increase in the plant load and reaches great values, still the plant efficiency attains its largest value at the full operating load. The reason can be explained by take a look to Fig. 5, where the ratio of exergy destruction for the three main components to input fuel exergy is shown. The analysis shows this ratio for the combustion chamber decreases from 48.46% at 40% design load to 40.73% for the full operating load, the same behavior is found for the other two components.

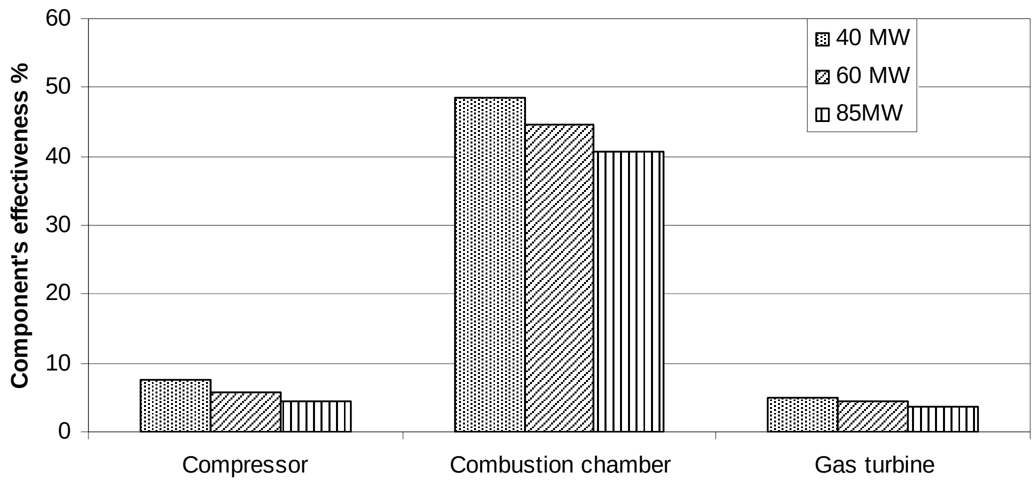

Figure 5. The Exergy destruction ratio, at different loads.

Exergoeconomic variables are evaluated for the plant components. The evaluation is based on the cost rates of the exergy streams. The average costs of the fuel per exergy unit of the fuel "$c_{F,k}$", the average costs of the product over exergy unit "$c_{P,k}$", the cost rate $\dot{C}_{D,k}$ associated with the exergy destruction, and the exergoeconomic factor f_k are illustrated. Those variables can be obtained only through a exergoeconomic analysis, while the cost rate associated with the capital investment and the operation and maintenance cost for each plant component $\dot{Z}_k$ is obtained from the economic analysis.

The cost rate formation within the unit GT14 is shown in Fig. 6. It is obvious that the cost rate for the net power increases with the increase in the power output, it is found the cost rate for net power output increases from 1051$/h at operating condition of 40% design load to 1383$/h at full operating load. The analysis shows that the cost rate of fuel exergy increases from 804$/h at 40% design load to 1205$/h at full operating load, because the rate of fuel consumption increases with the load. Since the unit operates more efficient as the full operating load being approached, it is found the cost rate of exergy of the product of combustion at turbine inlet decreases from 4979$/h at 40% design load to 3961$/h at full operating load, since the cost of the compressor work decreases from 3630$/h at 40% design load to 2211$/h at full operating load, and the cost rate of exergy of air leaving the compressor decreases from 4130$/h at 40% design load to 2710$/h with the full operating load. The cost rate of total exergy loss decreases from 798$/h at 40% design load to 868$/h at full operating load.

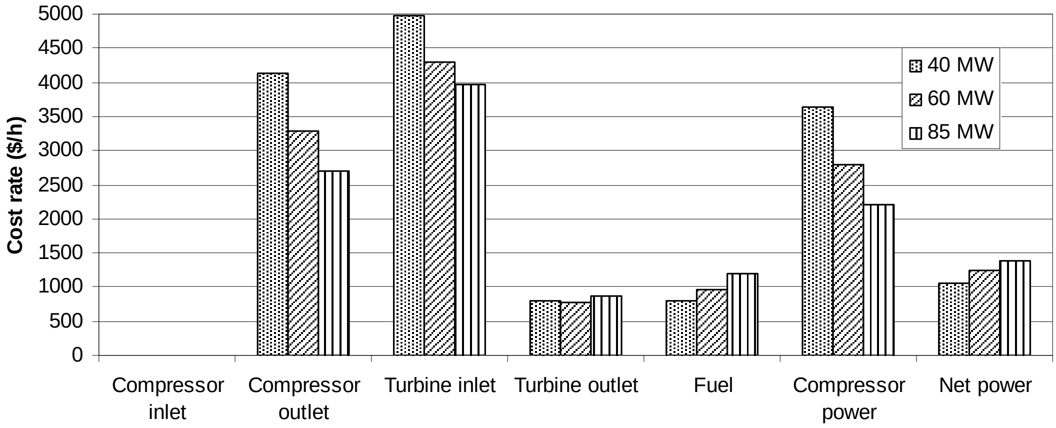

Figure 6. The cost rate formation within the unit GT14, at different load.

In Fig. 7, it can be seen that the average cost per unit exergy of the net power output and the average cost per unit compressor work input are equal (Product rule), and equals to 7.1$/GJ at operating conditions of 40% design load, 5.5$/GJ (60% design load), and at 4.4$/GJ (full operating load). The analysis shows that the cost per unit exergy of the total input fuel is constant for different loads and equals to 1.1$/GH, since the specific fuel exergy (kJ/kmol) is constant and equals to 8061030 kJ/kmole .

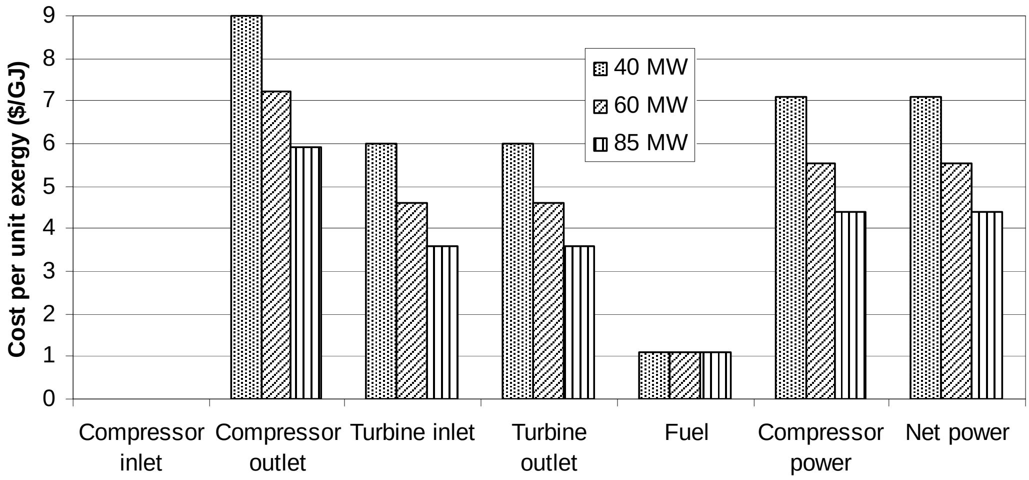

Figure 7. The specific costs per exergy unit for the streams the unit GT14, at different loads.

The cost associated with the removal of exergy for gas turbine is changing from 6 to 3.6$/GJ (Fuel rule). Also the cost per unit exergy of air leaving the compressor decreases from 9$/GJ at 40% design load to 6$/GJ at full operating load. The cost per unit exergy for all streams in the system is a function of the plant efficiency, where the cost per unit exergy for all streams is decreasing with the increase of the second low efficiency of the plant.

The cost of exergy destruction for the three main components is shown in Fig. 8. As expected, the cost of exergy destruction in the combustion chamber presents the main contribution to the total cost of exergy loss; because the rate of exergy destruction in the combustion chamber is much higher than that of the gas turbine and air compressor as shown in Fig. 4, its value varies in the combustion chamber from 1474$/h at 40% design load to 1123$/h at the full operating load. The contribution and the variation of cost of exergy destruction with load are lower for the other two main components. The cost of exergy destruction for each component decreases with the increase in load as a result of the decrease of the ratio of exergy flow rate with the load as shown in Fig. 5, and also because of the decrease of the cost per unit exergy of fuel with the load.

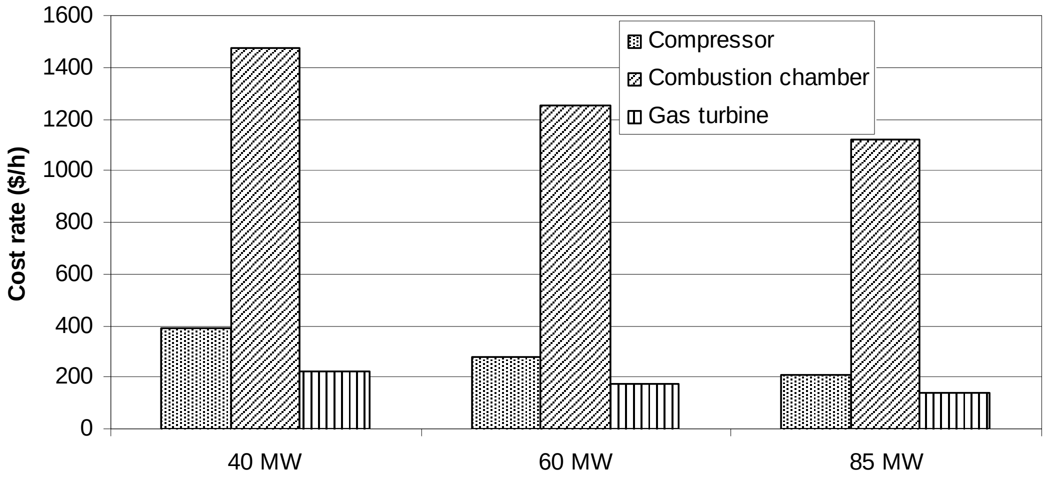

Figure 8. The Cost rate associated with Exergy destruction for the components the unit GT14, at different loads.

The exergoeconomic factor (*f*) is used to identify the major cost source (capital investment or cost of exergy destruction). Fig. 9 shows the values of the exergoeconomic factor for the three main components. The lowest value of the exergoeconomic factor is found for the combustion chamber due to the high rate of exergy destruction compared to other components which as shown on the Fig. 3, its value varies from 3% at 40% design load to 3.9% at the full operating load. For air compressor, the value of the exergoeconomic factor varies from 56.18% at 40% design load to 70.7% at the full operating load. The gas turbine has the highest value of exergoeconomic factor among all components; its value varies from 69.53% at 40% design load to 78.33% at the full operating load (the capital cost has the greater influence). Since the unit operates more efficient at the full operating load, the exergoeconomic factor increases as the full operating load being approached, since the cost of exergy destruction decreases with increasing load as shown in Fig. 8.

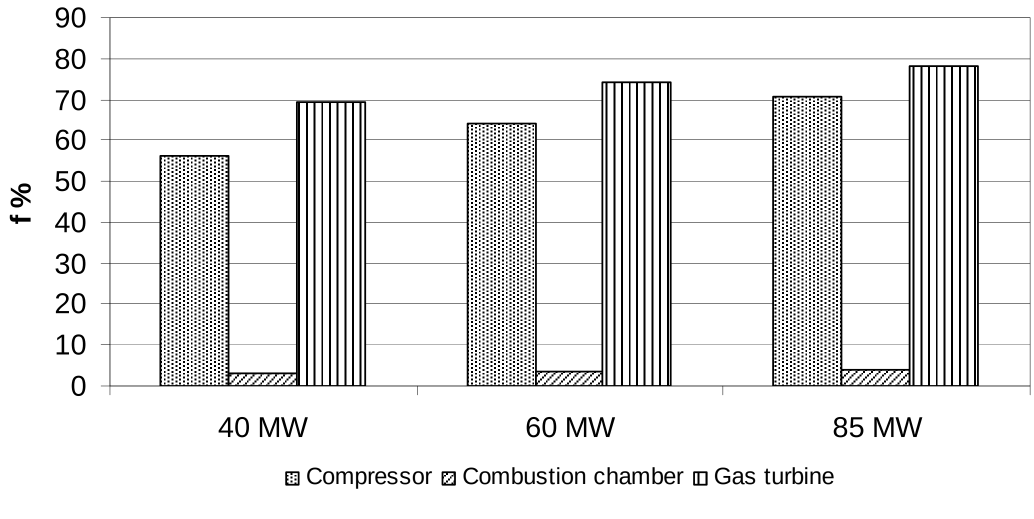

Figure 9. The Exergoeconomic factor f_k for the components the unit GT14, at different loads.

10. Conclusions

Exergoeconomic analysis is an effective tool used to evaluate the cost effectiveness of thermal systems, with the intent of evaluating and enhance the system performance from both economic and thermodynamics point of view. The analysis assists in the understanding of the cost value associated with exergy destroyed in a thermal system, and hence provides energy system's designers and operators with the information, necessary for operating, maintaining, and evaluating the performance of energy systems.

Exergoeconomic analysis is performed for the unit GT14 of south Tripoli gas turbine power plant. The following conclusions are drawn:.

1. The cost of each product generated by unit GT14 is calculated, and the cost formation process and the flow of costs in the system are analyzed.
2. The average cost per unit exergy for final products of the plant is identified (net power).

3. The combustion chamber has the highest cost value of exergy destruction among all components and has the lowest value of the exergoeconomic factor *f*.
4. Exergoeconomic analysis shows that unit GT14 attains its maximum performance at the full operating load.
5. As *f* factor decreases with the increasing load, part load operation must be minimized as much as possible.
6. Exergoeconomic analysis is a powerful tool that can be adopted for the performance evaluation of different thermal systems in Libya.

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Appendix

Table A-1: The thermodynamic data of the plant.

State	40%			60%			Full operating load		
	m˙ Kg/s	P bar	T K	m˙ Kg/s	P bar	T K	m˙ Kg/s	P bar	T K
1	422.32	1.023	299.75	404.31	1.023	301.3	394.48	1.023	303
2	422.32	9.8	635.45	404.31	10.4	644.10	394.48	11.0	655.90
3	426.554	9.8	1029.15	409.371	10.4	1129.0	400.829	11.0	1263.0
4	426.554	1.023	621	409.371	1.023	681.0	400.829	1.023	762.0
Fuel	4.234	12	298	5.061	12	298	6.349	12	298

Table A-2: The exergy balance of the unit GT14 components.

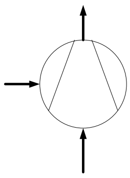
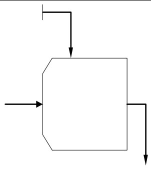
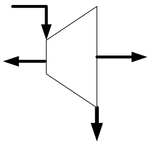
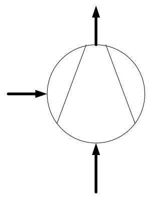
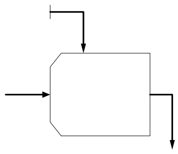
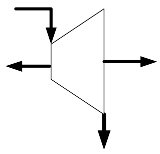
component	Schematic	Exergy balance	Additional information
Air Compressor (AC)		$\Psi_1 + W_C = \Psi_2 + I_{D,AC}$	Air supplied at zero exergy $\Psi_1 = 0$ $\Psi_P = \Psi_2 - \Psi_1$ $\Psi_F = W_{AC}$
Combustion chamber (CC)		$\Psi_{fuel} + \Psi_2 = I_{D,CC} + \Psi_3$ $\frac{\Psi_{fuel}}{LHV} \cong 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a}$	$\Psi_P = \Psi_3$ $\Psi_F = \Psi_f + \Psi_2$
Gas turbine (GT)		$I_{D,GT} = \Psi_3 - \Psi_4 - W_{GT}$	$\Psi_P = W_{GT}$ $\Psi_F = \Psi_3 - \Psi_4$

Table A-3: The cost balance and auxiliary equation of the plant components

component	Schematic	Cost balance	Additional information
Air Compressor (AC)		$C_1 + C_{AC} - C_2 + Z_{AC} = 0$	Air supplied at zero cost $c_1 = 0$ $c_F = \left(\frac{C_{AC}}{W_{AC}}\right)$ $c_P = \left(\frac{C_2}{\Psi_2}\right)$
Combustion chamber (CC)		$C_2 + C_{Fuel} - C_3 + Z_{CC} = 0$	Combustion process in the chamber is complete, auxiliary equations are not required $c_P = c_3$ 2 $c_F = \left(\frac{C_{Fuel} + C_2}{\Psi_{Fuel} + \Psi_2}\right)$
Gas turbine (GT)		W $C_3 - C_{net} - C_{AC} + Z_{GT} = 0$	One auxiliary equation required $c_P = \left(\frac{C_{AC} + C_{net}}{W_{AC} + W_{net}}\right)$ $c_F = \left(\frac{C_3 - C_4}{\Psi_3 - \Psi_4}\right)$

1

Table 1: Economic Data for the unit GT14.

Component	PEC* (10^3\$)	$\dot{Z}^{OM}$	$\dot{Z}^{CI}$	$\dot{Z}$
Combustion Chamber	264	43	C_f 2.17	48
Gas Turbine	2916	477 2	24	501
Air Compressor	2913	476	24	500 3

3

W_{net}

W_{AC}

4