Exergoeconomic Analysis of Gas Turbine Power Plants

Mofid Gorji-Bandpy and Vahid Ebrahimian

www.serd.ait.ac.th/reric

Abstract *- The main purpose of this paper is to apply the thermoeconomics concepts to a projected gas turbine system, which aims at providing the electrical demand of an industrial district sited in Mahshahr, Iran. A unit exergy cost is assigned to each disaggregated exergy in the streams at any state. This methodology permits us to obtain a set of equations for the unit costs of the system and to each junction. The monetary evaluations of various exergy costs are obtained by solving the set of equations. The comparison analysis between typical exergy-costing methodologies was also evaluated.*

Keywords **- Exergy, Gas-turbine, Irreversibility, Exergoeconomic**

1. INTRODUCTION

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. Furthermore, exergoeconomic analysis estimates the unit cost of product such as electricity and quantifies monetary loss due to irreversibility. At present, such analysis is in great demand because proper estimation of the production costs is essential for companies to operate profitably.

The development and application of exergoeconomics have provided a theoretical basis for designing efficient and cost-effective energy-conversion systems. Since the 1950s, exergoeconomics has been described in extensive studies and applications [1-3]. A large number of exergoeconomic methods emerged in the 1980s and were applied to the energy systems. Examples include the exergoeconomic analysis and evaluation method of Tsatsaronis [4], the exergetic cost theory of Valero [5], the engineering function analysis of Spakovsky [6], and the thermoeconomic function method of Frangopoulos [7]. With the development of technology and economic analysis, we are able to implement industrial processes that approach ideality more closely than in the past and have higher energy-utilization efficiencies.

In this study, exergetic and thermoeconomic analyses were performed for the 117-MW gas turbine plant, which is shown in Fig.1. In these analyses, mass and energy conservation laws were applied to each component. Quantitative balance of the exergies and exergy costs for each component and for the whole system was carefully considered. The exergy-balance equation developed by Oh [8] and the corresponding exergy cost-balance equation developed by Kim [9] were used in these analyses.

2. THE GAS TURBINE PLANT

A schematic of a 117-MW gas turbine system is given in Fig. 1 and shows the main work and exergy flows and the state points which we accounted for in this analysis. The system consists of an air-compressor (AC), a combustion chamber (CC), an air-preheater (APH), and a gas- turbine (GT). A typical mass flow rate of air to the compressor at $26°C$ is 497 $kg \cdot s^{-1}$ and the air-fuel ratio at full load is about 50 on a mass basis.

The air comes from an environment that has a temperature of $26\ °C$ and a pressure of 1.013 bar. The pressure increases to 8.611 bar through the compressor, which has an isentropic efficiency of 83 percent.

The inlet temperature to the turbine is $1047.85\ °C$. The turbine has an isentropic efficiency of 88 percent. The regenerative heat exchanger has a heat exchanger effectiveness of 75 percent.

The pressure drop through the air pre heater is 4 percent of the inlet pressure for both flow streams and through the combustion chamber is 3 percent of the inlet pressure. The fuel, which is natural gas, has a temperature of $26\ °C$ and a pressure of 30 bar. The outlet pressure of the air pre heater in gas stream is 1.032 bar.

3. COST EQUATION FOR PLANT COMPONENTS

All costs due to owning and operating a plant depend on the type of financing, required capital, expected life of a component, etc. The annualized (levelized) cost method of Moran [10] is used here. Using the capital recovery factor *CRF (i, n)*, the annualized cost may be written as

$$\dot{C}\,(\$/\,year) = \left[I-(SV)PWF(i,n)\right]CRF(i,n) \tag{1}$$

where $SV = 0.1I$, $CRF(i,n) \equiv i/1-(1+i)^{-n}$ and $PWF(i,n) \equiv (1+i)^{-n}$

Mofid Gorji-Bandpy, Associat Professor, School of Mechanical Engineering, University of Mazandaran, P.O. Box 484, Babol, 47144, Iran (Phone/Fax: +98-111-3234205; e-mail: gorji@nit.ac.ir), corresponding author.

Vahid Ebrahimian, School of Mechanical Engineering, University of Mazandaran, P.O. Box 484, Babol, 47144, Iran.

Dividing the levelized cost by 8000 annual operating hours, we obtain the following capital cost rate for the *k*th component of the plant:

$$\dot{Z}_k \; (\$/s) = \frac{\phi_k \, \dot{C}_k}{3600 \times 8000} \tag{2}$$

The maintenance cost is taken into consideration through the factor $\phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years and the interest rate is 23.5%. The number of hours of plant operation per year and the maintenance factor utilized in this study are the typical numbers employed in standard exergoeconomic analysis [7].

4. COST-BALANCE EQUATIONS FOR THE GAS TURBINE PLANT

Several methodologies for the exergy-costing of the product are available at present. A comparison between various exergy-costing methodologies is needed to find a single method of exergoeconomic analysis. The specific-cost exergy costing (SPECO) method with the average cost approach which was recommended by Lazzaretto and Tsatsaronis [11] for the exergoeconomic analysis of thermal systems and the modified productive structure analysis (MOPSA) of thermal systems, which was developed by Kim [9] and the Moran method [10] were utilized for the purpose.

Brief account of SPECO, MOPSA and Moran methodologies for the gas turbine system was made in this section.

4.1 SPECO Method

A brief summary of the SPECO methodology is given in the following. For a more detailed description see the paper by Lazzaretto and Tsatsaronis [12]. The two main purposes of the methodology are too objectively

- define a fuel, a product and thus an exergetic efficiency for each component, and
- formulate the required auxiliary cost equations.

These purposes are not independent but interrelated. The fuel and product of the components are formulated through the following procedure:

(1) The exergy carriers, consisting of all material and energy streams are identified.

(2) Depending on the purpose of the study, the total exergy or any of its components (e.g., thermal, mechanical and chemical exergies) are considered.

(3) The exergy streams are separated into two categories:
   - Continuous exergy streams, and
   - Interrupted exergy streams.

(4) At this point the fuel and the product for each component are defined using the following criteria:
   - For continuous exergy streams, every decrease in an exergy stream between the inlet and the outlet of the component is included in the fuel whereas every exergy increase between the inlet and the outlet of the component is included in the product.
   - For interrupted exergy streams, the exergy at the inlet of the component belongs to the fuel, and the exergy at the outlet of the component is part of the product.

This is an easy, objective and unambiguous approach for defining the fuel and product for each component. The SPECO methodology suggests using the following auxiliary cost equations:

On the fuel side

- For continuous exergy streams the F rule is applied, whereas
- For interrupted exergy streams no cost equation is necessary.

On the product side

- For continuous exergy streams the P rule is used, and
- For interrupted exergy streams the P postulate, is applied.

The F rule is based on the simple concept that the cost removal from a stream by a component must be equal to the cost at which the removal exergy was previously supplied to that stream. For the average cost approach and continuous exergy streams, the F rule is expressed as [13]

$$c^X_{F,k} \sum_{y=1}^{NS} (\dot{B}^X_{in,k,y} - \dot{B}^X_{out,k,y}) = \sum_{y=1}^{NS} c^X{}_{in,k,y} \left(\dot{B}^X{}_{in,k,y} - \dot{B}^X{}_{out,k,y} \right) \tag{3}$$

where X represents the exergy form, k the component, and y the exergy stream. NS is the total number of exergy streams of the Xth exergy form entering the kth component. The average cost $c^X_{F,k}$ is defined as

$$c^X_{F,k} = \frac{\sum_{y=1}^{NS} (\dot{C}^X_{in,k,y} - \dot{C}^X_{out,k,y})}{\sum_{y=1}^{NS} (\dot{B}^X_{in,k,y} - \dot{B}^X_{out,k,y})} \tag{4}$$

$\dot{B}^X_{out,k,y}$ and $\dot{C}^X_{out,k,y}$ are the exiting exergy and cost rates, respectively, associated with the Xth exergy form of the yth material or energy stream, which enters the kth component with the respective values $\dot{B}^X_{in,k,y}$ and $\dot{C}^X_{in,k,y}$.

The P rule states that each exergy unit is supplied to all the streams associated with the product of the kth component at the same average cost. Thus, for continuous exergy streams y and x we write:

$$c^M_{P,k,y} = c^T_{P,k,y} = c^{CH}_{P,k,y} = c_{P,k} \tag{5}$$

and

$$c^M_{P,k,x} = c^M_{P,k,y} = c_{P,k} \; ; \quad c^T_{P,k,x} = c^T_{P,k,y} = c_{P,k} \; ; c^{CH}_{P,k,x} = c^{CH}_{P,k,y} = c_{P,k} \tag{6}$$

Here $c_{P,k}$ is the cost per exergy unit of the product for the kth component.

The P postulate derives directly from the P rule and is applied when at least one interrupted exergy stream participates in the definition of the product: If both the Xth and Zth exergy forms of the *same* material stream at the outlet (y) are interrupted, the auxiliary equation to be used for this stream is

$$c^{X}_{out,k,y} = c^{Z}_{out,k,y} \tag{7}$$

For the same exergy form (X) of two *different interrupted* outlet streams (y and x) we can write

$$c^{X}_{out,k,y} = c^{X}_{out,k,x} \tag{8}$$

If the Xth exergy form of the yth material stream is continuous and is part of the product and the Zth exergy form (of the xth material stream) being also part of the product is interrupted, then we use

$$c^{X}_{P,k,y} = c^{Z}_{P,k,x} \tag{9}$$

Using the SPECO method with the average cost approach one may obtain the following cost-balance equations for each component of the gas turbine system. These are

- *Air compressor*

$$\begin{aligned} &\dot{m}_a d_1^M + \dot{m}_a d_1^T + \dot{C}_8^W \\ &- \dot{m}_a d_2^M - \dot{m}_a d_2^T + \dot{Z}_{AC} = 0 \end{aligned} \tag{10}$$

- *Air preheater*

$$\begin{aligned} &\dot{m}_a d_2^M + \dot{m}_a d_2^T + \dot{m}_g d_6^M + \dot{m}_g d_6^T \\ &- \dot{m}_a d_3^M - \dot{m}_a d_3^T - \dot{m}_g d_7^M - \dot{m}_g d_7^T + \dot{Z}_{APH} = 0 \end{aligned} \tag{11}$$

- *Combustion chamber*

$$\begin{aligned} &\dot{m}_a d_3^M + \dot{m}_a d_3^T + \dot{m}_f d_4^M + \dot{m}_f d_4^T \\ &+ \dot{m}_f d_4^{CH} - \dot{m}_g d_5^M - \dot{m}_g d_5^T + \dot{Z}_{CC} = 0 \end{aligned} \tag{12}$$

- *Gas turbine*

$$\begin{aligned} &\dot{m}_g d_5^M + \dot{m}_g d_5^T - \dot{m}_g d_6^M \\ &- \dot{m}_g d_6^T - \dot{C}_9^W + \dot{Z}_{GT} = 0 \end{aligned} \tag{13}$$

The numbers in subscripts denote the states of material and energy streams described in figure 1. Now we have 17 unknowns with only four cost-balance equations. Auxiliary equations for exergy costing can be obtained by applying F and P rules to each component. These are

- *Air compressor*

$$\frac{d_2^T - d_1^T}{b_2^T - b_1^T} = \frac{d_2^M - d_1^M}{b_2^M - b_1^M} \quad \text{P-rule} \tag{14}$$

- *Air preheater*

$$c_3^M = c_2^M \quad \text{F-rule} \tag{15}$$

$$c_6^M = \frac{\dot{m}_a c_2^M + \dot{m}_f c_4^M}{\dot{m}_a + \dot{m}_f} \quad \text{F-rule} \tag{16}$$

$$c_6^M = c_7^M \quad \text{F-rule} \tag{17}$$

$$c_6^T = c_7^T \quad \text{F-rule} \tag{18}$$

- *Combustion chamber*

$$c_5^M = \frac{\dot{m}_a c_3^M + \dot{m}_f c_4^M}{\dot{m}_a + \dot{m}_f} \quad \text{F-rule} \tag{19}$$

- *Gas turbine*

$$c_5^T = c_6^T \quad \text{F-rule} \tag{20}$$

$$c_5^M = c_6^M \quad \text{F-rule} \tag{21}$$

$$c_8^W = c_9^W \quad \text{F-rule} \tag{22}$$

The remaining 4 equations for the cost accounting calculations may be obtained by considering the availability of the material streams and fuel at inlet and outlet conditions of the overall system. Or

$$d_1^M = d_1^T = d_4^T = 0 \tag{23}$$

$$d_4^{CH} = c_4^{CH} b_4^{CH} \quad \text{with}$$

$$c_4^{CH} = 1.95 \times 10^{-6}\ \$/kJ \tag{24}$$

Solving the above 17 equations simultaneously, one may obtain the cost flow rates and average unit costs at each inlet and outlet of the component.

4.2 MOPSA Method

The exergy-balance equation is written as [8]

$$\dot{B}^{CHE} + \left(\sum_{inlet}\dot{B}_i^{\,T} - \sum_{outlet}\dot{B}_e^{\,T}\right) + \left(\sum_{inlet}\dot{B}_i^{\,P} - \sum_{outlet}\dot{B}_e^{\,P}\right) + T_0\left(\sum_{inlet}\dot{S}_i - \sum_{outlet}\dot{S}_e + \frac{\dot{Q}_{CV}}{T_0}\right) = \dot{B}^W \qquad (25)$$

The fourth term represents the rate of entropy loss. The term $\dot{B}^{CHE}$ denotes the rate of exergy flow of fuel in the plant.

Assigning unit exergy cost to each decomposed exergy in the stream, the cost-balance equation corresponding to the exergy-balance equation given in Eq. (25) may be written as [9]

$$\begin{aligned} &\dot{B}^{CHE} c_f + \left(\sum_{inlet}\dot{B}_i^{\,T} - \sum_{outlet}\dot{B}_j^{\,T}\right)c_T \\ &+ \left(\sum_{inlet}\dot{B}_i^{\,P} - \sum_{outlet}\dot{B}_j^{\,P}\right)c_P \\ &+ T_0\left(\sum_{inlet}\dot{S}_i - \sum_{outlet}\dot{S}_j + \frac{\dot{Q}_{CV}}{T_0}\right)c_S \\ &+ \dot{Z}_{(k)} = \dot{B}^W c_W \end{aligned} \qquad (26)$$

The term $\dot{Z}_{(k)}$ includes all financial charges associated with owning and operating the kth plant component. Eqs. (25) and (26) are two basic equations used in the MOPSA method for exergy costing of products.

By assigning a unit exergy cost to each disaggregated exergy in the stream at any state, as described in Eq. (26), one may reduce considerably the variables involved in the cost formation process. The cost-balance equations for each component of gas turbine system can be obtained with help of Eq. (26). When the cost-balance equation is applied to a component, a new unit cost must be assigned to the component's principal product. Assigning a new unit cost is crucial in the exergy-costing method based on the productive structure analysis. For example, an air compressor is a component that uses electricity to increase the mechanical exergy of air; the method assigns a new unit cost of c_{IP} to the mechanical exergy of air, the component's main product [14]. After unit cost is assigned to the respective principal product of components, the cost-balance equations for these components are as follows.

- *Air compressor*

$$\begin{aligned} &(\dot{B}_1^T - \dot{B}_2^T)c_T + (\dot{B}_1^P - \dot{B}_2^P)c_{IP} \\ &+ T_0(\dot{S}_1 - \dot{S}_2)c_S + \dot{Z}_{AC} = \dot{B}_8^W c_W \end{aligned} \qquad (27)$$

- *Air preheater*

$$\begin{aligned} &\left(\dot{B}_2^{\,T} - \dot{B}_3^{\,T}\right)c_{IIT} + \left(\dot{B}_6^{\,T} - \dot{B}_7^{\,T}\right)c_T \\ &+ \left(\dot{B}_2^{\,P} - \dot{B}_3^{\,P} + \dot{B}_6^{\,P} - \dot{B}_7^{\,P}\right)c_P \\ &+ T_0\left(\dot{S}_2 - \dot{S}_3 + \dot{S}_6 - \dot{S}_7 + \frac{\dot{Q}_{APH}}{T_0}\right)c_S + \dot{Z}_{APH} = 0 \end{aligned} \qquad (28)$$

- *Combustion chamber*

$$\begin{aligned} &\dot{B}_4^{\,CHE} c_f + \left(\dot{B}_3^{\,T} + \dot{B}_4^{\,T} - \dot{B}_5^{\,T}\right)c_{IIIT} \\ &+ \left(\dot{B}_3^{\,P} + \dot{B}_4^{\,P} - \dot{B}_5^{\,P}\right)c_P \\ &+ T_0\left(\dot{S}_3 + \dot{S}_4 - \dot{S}_5 + \frac{\dot{Q}_{CC}}{T_0}\right)c_S + \dot{Z}_{CC} = 0 \end{aligned} \qquad (29)$$

- *Gas turbine*

$$\begin{aligned} &(\dot{B}_5^T - \dot{B}_6^T)c_T + (\dot{B}_5^P - \dot{B}_6^P)c_P \\ &+ T_0(\dot{S}_5 - \dot{S}_6)c_S + \dot{Z}_{GT} = \dot{B}_9^W c_W \end{aligned} \qquad (30)$$

Two more cost-balance equations can be obtained from the junctions for the thermal and mechanical exergies. These are

$$\begin{aligned} &(\dot{B}_2^T + \dot{B}_4^T - \dot{B}_5^T)c_T = (\dot{B}_2^T - \dot{B}_3^T)c_{IIT} \\ &+ (\dot{B}_3^T + \dot{B}_4^T - \dot{B}_5^T)c_{IIIT} \end{aligned} \qquad (31)$$

$$c_P = c_{IP} \qquad (32)$$

A remaining cost-balance equation which is most important in the evaluation of the unit cost of product may be obtained by considering the exergy and entropy flow streams entering and leaving the total system. It is

$$\begin{aligned} &(\dot{B}_1^T + \dot{B}_4^T - \dot{B}_7^T)c_T + (\dot{B}_1^P + \dot{B}_4^P - \dot{B}_7^P)c_P \\ &+ T_0(\dot{S}_1 + \dot{S}_4 - \dot{S}_7)c_S = 0 \end{aligned} \qquad (33)$$

Now one may obtain the unit cost of product c_W by solving the foregoing 7 equations simultaneously given fuel cost of c_f.

4.3 Moran Method

In this method for a plant having a single fuel input which at steady-state produces a single output product in the form of electricity, the cost of the fuel consumed over any time period is assumed to be a significant fraction of the total cost for that period. For such a plant it is convenient to represent the annualized cost of producing the product as a sum of the fuel cost and costs for creating and maintaining the plant.

Introducing a second law efficiency for the plant in the form (output/input), $\eta_b = \dot{B}^W / \dot{B}^{CHE}$, the product cost can be obtained as [10].

$$c_W = \frac{c_f}{\eta_b}\left[1 + \frac{\sum \dot{Z}_k}{c_f\, \dot{B}_4^{CHE}}\right] \qquad (34)$$

In this equation, production cost depends heavily on fuel cost and the exergetic efficiency of the system and is affected by the ratio of the monetary flow rate of non-fuel items to the monetary flow rate of fuel items.

5. RESULTS AND DISCUSSIONS

Table 1 shows chemical, thermal and mechanical exergy flow rates and entropy flow rates at various state points shown in figure 1. These flow rates were calculated based on the values of measured properties such as pressure, temperature, and mass flow rate at various points in the gas turbine power plant sited in Mahshahr, Iran.

The net flow rates of the various exergies crossing the boundary of each component in the gas-turbine plant at 100% load condition are shown in table 2. The exergy destruction in each component is also given in this table.

Positive values of exergies indicate the exergy flow rate of products while negative values represent the exergy flow rate of resources or fuel. Here, the product of a component corresponds to the added exergy whereas the resource to the consumed exergy [11].

The sum of the exergy flow rates of products and resources and destruction equals zero for each component and for the total plant; this zero sum indicates that perfect exergy balances are satisfied.

In table 3, the initial investments, the monetary flow rates, and the capital cost rate for each component of the 117-MW gas turbine power plant are given. The unit exergy cost of product has been obtained. The salvage value after 15 years was taken as 10% of the initial investment in this study. Calculation was done at full load condition with the electric output of 116.010 MW.

The production costs obtained from SPECO, MOPSA and Moran methods for the gas turbine system are shown in table 4. We can compare the production costs estimated from the three methods of exergoeconomic analysis. The results indicated that the relative deviation in the production costs evaluated from SPECO and MOPSA methods is about 10%. The relative deviation between SPECO and Moran methods is also about 10%, but the relative deviation between MOPSA and Moran methods is about 20%. The unit cost of electricity for the gas turbine system is lower when Moran method is used.

The Moran method is simpler than SPECO and MOPSA methods, but its result has deviation to the results of those two methods. Also the Moran method can be used only in one case and it is when the power plant produces only one product, but we can use the MOPSA and SPECO methods for power plants that produce more than one product.

The MOPSA method is simpler than SPECO method and its result is also near to the result of the SPECO method. Therefore, we can select it as the best method.

6. FIGURES AND TABLES

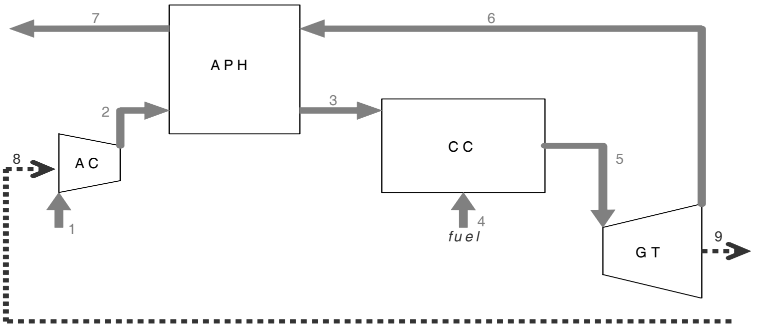

Fig. 1. Gas turbine system.

Table 1. Property Values and Chemical, Thermal, and Mechanical Exergy Flows and Entropy Production Rates at Various State Points in the Gas Turbine Plant at 100% Load Conditions

State	$\dot{m}\ (kg/s)$	$T\ (K)$	$P\ (bar)$	$\dot{B}^{CHE}\ (MW)$	$\dot{B}^{T}\ (MW)$	$\dot{B}^{P}\ (MW)$	$\dot{S}\ (MW/K)$
1	497.00	299.15	1.013	0.000	0.000	0.000	0.000
2	497.00	603.02	8.611	0.000	47.034	91.318	0.045
3	497.00	796.91	8.267	0.000	102.221	89.580	0.190
4	10.09	299.15	30.000	508.566	0.000	5.298	−0.018
5	507.09	1320.0	8.019	0.000	335.766	91.015	0.563
6	507.09	861.54	1.075	0.000	143.181	2.613	0.607
7	507.09	695.18	1.032	0.000	83.699	0.817	0.488

Table 2. Net Exergy Flow Rates and Exergy Destruction in the Gas Turbine Plant at 100% Load Conditions

Component	$\dot{B}^{W}\ (MW)$	$\dot{B}^{CHE}\ (MW)$	$\dot{B}^{T}\ (MW)$	$\dot{B}^{P}\ (MW)$	$\dot{B}_{D}\ (MW)$
Compressor	−151.814	0.000	47.034	91.318	13.462
Air pre heater	0.000	0.000	−4.295	−3.534	7.829
Combustion chamber	0.000	−508.566	233.545	−3.863	278.884
Gas turbine	267.824	0.000	−192.585	−88.402	13.163
Total plant	116.010	−508.566	88.699	−4.481	313.338

Table 3. Initial Investments, Monetary Flow Rates, and Capital Cost Rates in the 117-MW Gas Turbine Power Plant

Component	I $(\times 10^{6}\ \$)$	$\dot{C}$ $(\times 10^{6}\ \$/year)$	$\dot{Z}$ $(\times 10^{-4}\ \$/s)$
AC	9.69	2.36	869
APH	0.7	0.171	63
CC	0.97	0.236	87
GT	39.17	9.56	3519

Table 4. The Production Costs Obtained from SPECO, MOPSA and Moran Methods

Method	c_W $(\$/GJ)$	c_W $(\$/kW.hr)$
SPECO	8.55	0.031
MOPSA	9.57	0.034
Moran	7.28	0.026

7. CONCLUSIONS

An exergy balance applied to a process or a whole plant tells us how much of the usable work potential, or exergy, supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process. The loss of exergy, or irreversibility, provides a generally applicable quantitative measure of process inefficiency.

Several methodologies for the exergy-costing of the product are available at present. A comparison between various exergy-costing methodologies is needed to find a single method of exergoeconomic analysis. The SPECO method, the MOPSA method and the Moran method were utilized for the purpose and have been applied to the 117-MW gas turbine power plant. The production costs estimated from the three methods of exergoeconomic analysis were compared. The results indicated that the MOPSA method is the best method for estimate the unit cost of electricity produced from gas turbines.

8. NOMENCLATURE

b	Specific exergy (MW/kg)
$\dot{B}$	Rate of exergy flow (MW)
c	Cost per exergy unit $(\$/GJ)$
$CRF(i,n)$	Capital recovery factor
$\dot{C}$	Monetary flow rate $(\$/year)$
d	Cost per unit mass $(\$/kg)$
i	Interest rate
I	Initial investment cost $(\$)$
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure
$PWF(i,n)$	Present worth factor
$\dot{Q}$	Heat transfer rate
SV	Salvage value
$\dot{S}$	Entropy flow rate (MW/K)
T	Temperature (K)
T_0	Ambient temperature
$\dot{Z}_k$	Capital cost rate of unit k $(\$/s)$

Greek Letters

ϕ_k	maintenance factor
η_b	exergy efficiency

Subscripts

a	Air
f	Fuel

g	Combustion gas
in	Inlet
k	System component
out	Outlet
x	Material stream
y	Material stream
0	Standard state
AC	Air compressor
APH	Air pre heater
CC	Combustion chamber
D	destruction
GT	gas turbine

Superscripts

CHE	Chemical
P	Mechanical
T	Thermal
W	Power
X	Xth exergy form
Z	Zth exergy form

9. ACKNOWLEDGEMENT

The authors thank to Mohammad J. Ebadi for his precious collaboration.

10. REFERENCES

[1] Y. El-Sayed, A critical review of second law costing methods, *J. Engr. for Power*, Vol.92, pp. 27-34 (1997).

[2] R. Gaggioli, Efficiency and costing; second law analysis of processes, *Energy-The International Journal*, Vol.5, pp. 865-873, (1980).

[3] R. Evans, On the use of exergy and thermoeconomics in the design of desalination, *Energy-The International Journal*, Vol.5, pp. 805 812, (1980).

[4] G. Tsatsaronis, On exergy costing in exergoecono-mics, AES-Vol.21, pp. 1-11, (1990).

[5] A. Valero, Methods for the exergy-costing of the products, *Energy-The International Journal*, Vol.19, pp. 365-377, (1994).

[6] M. Von Spakovsky, Application of engineering functional analysis to the analysis and optimization of the CGAM problem, *Energy The International Journal*, Vol.19, pp 343-364, (1994).

[7] C. Frangopoulose, CGAM problem: definition and conventional solution, *Energy-The International Journal*, Vol.19, pp. 279-286, (1994).

[8] S. Oh, Exergy analysis for a gas-turbine cogeneration system, *J. Eng. Gas Turb. Power*, Vol.118, pp. 782-791, (1996).

[9] S. Kim, Exergoeconomic analysis of thermal systems, Energy, Vol.23, pp. 393-406, (1998).

[10] J. Moran, *Availability analysis: a guide to efficient energy use*, Prentice-Hall, pp. 199-215, (1982).

[11] A. Lazzaretto and Tsatsaronis, On the quest for objective equations in exergy costing, AES, Vol.37, pp. 197-210, (1997)

[12] A. Lazzaretto and Tsatsaronis, A general process based methodology for exergy costing, *Proceedings of the ASME Advanced Energy Systems Division*, Atlanta, pp. 413-428, (1996).

[13] G. Tsatsaronis, Exergoeconomic analysis and evaluation of energy conversion plants, *Energy The International Journal*, Vol.10, pp. 81-94, (1985).

[14] H. Kwak, Exergetic and thermoeconomic analysis of power plants, energy, Vol. 28, pp. 343-360, (2003).