AVOIDABLE AND UNAVOIDABLE EXERGY DESTRUCTIONS AND THE ASSOCIATED INVESTMENT COST FOR EVALUATING THE PERFORMANCE OF A GAS TURBINE CYCLE

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الملخص

الهدف من العمل الحالي هو توفير وعي أعمق حول الأداء الديناميكي الحراري وفعالية التكلفة للمنظومات الحرارية. وللبحث عن إمكانية التحسين، يجب تحديد الجزء الذي يمكن تجنبه من تحطيم الإكسيرجي وتكلفة الاستثمار التي يمكن تجنبها.

ينقسم تحطيم الإكسيرجي والتكلفة الاستثمارية المرتبطة بها إلى جزائين احدهما يمكن تجنبه وأخر لا يمكن تجنبه. يتم في هذا العمل تقديم فعالية معدّلة وعامل اقتصادي-حراري معدّل ومقارنتهما مع الفعالية والعامل الأقتصادي-الحراري التقليديين.

تم أخذ دورة تربينة غازية بسيطة كمثال لاستكشاف مميزات هذه المقاربة ولإعطاء حكم منطقي لأداء المنظومات الحرارية. أظهرت النتائج أنه بالنسبة للدورة بأكملها، كان العامل الاقتصادي-الحراري الكلي التقليدي 16.15٪ والفعالية التقليدية 24.67٪، في حين كان العامل الاقتصادي-الحراري الكلي المعدّل 36.85٪، والفعالية المعدّلة 40.14٪.

ABSTRACT

The objective of the current work is to provide a deeper awareness about the thermodynamic performance and cost effectiveness of thermal systems. To seek the potential for improvement, the avoidable part of the exergy destruction and the avoidable investment cost must be identified. The exergy destruction and the associated investment cost are split into avoidable and unavoidable parts. Modified exergatic efficiency (effectiveness) and a modified exergoeconomic factor are introduced and compared with the corresponding conventional effectiveness and exergoeconomic factor.

A simple gas turbine cycle is taken as an example to explore the advantages of such approach to give a rational judgment of the performance of thermal systems. The results show that, for the whole plant the conventional exergoeconomic factor is calculated as 16.15% and the conventional effectiveness as 24.67%, while the modified exergoeconomic factor is calculated as 36.85%, and the modified effectiveness as 40.14%.

KEYWORDS: Thermoeconomic; exergoeconomic factor, effectiveness, avoidable exergy destruction; unavoidable exergy destruction

INTRODUCTION

The thermoeconomic methodology is adopted by many authors, where the production cost is allocated on the component level [1]. The thermoeconomic approach allows engineers to evaluate the cost of consumed resources, money, and system exergy destruction "irreversibilities" in terms of the overall production and enables them to exploit these resources effectively. By allocating costs to flow streams in each process, thermoeconomic helps in the assessment of the economic effect of exergy destruction [2].

An advanced thermodynamic analysis has been developed to overcome the limitations of the conventional analyses and to increase our knowledge about the rational thermodynamic performance of thermal processes and systems [3]. To be realistic in evaluating the thermodynamic performance of thermal systems, exergy destruction should be split into two distinguishing parts, avoidable and unavoidable exergy destruction.

An advanced exergy/exergoeconomic analysis to be used instead of conventional exergy/exergoeconomic analyses [4]. The unavoidable part is caused due to technological and economical limitations. Avoidable investment cost is associated with the avoidable exergy destruction, enhancement efforts should then emphasis only on these avoidable parts [4]. The additional splitting of exergy destruction into its avoidable and unavoidable constituents exposes a more accurate assessment of the enhancement potential of the considered system [5]. The greater part of the exergy destructions detected in a system could be avoidable and could be minimized by improvements in the design [6].

Advanced exergatic and thermoeconomic analyses are desirable in order to conclude which part of the inefficiencies and the associated costs is produced by component exchanges, and which part can be avoided through technological advances of a plant [7]. Exergy destruction term can be further split into its endogenous and exogenous parts. By grouping of the allocated parts of exergy destruction, four dissimilar exergy destruction terms are acquired: avoidable endogenous, avoidable exogenous, unavoidable endogenous and unavoidable exogenous. The summation of them composes exergy destruction [8].

An avoidable and unavoidable exergy analysis applied to a plant that uses geothermal energy in the form of a cascade to produce electricity, cold and useful heat is presented [9]. The results found through the unavoidable and ideal conditions are very significant to have strategies for upcoming technological advances in the cascade geothermal plant.

A conventional and advanced exergy analysis of a turbofan engine is analyzed [10]. The exergy destruction rates within the engine components are split into endogenous/exogenous and avoidable/unavoidable parts. The results show that small improvement potential as the unavoidable exergy destruction rate is 90% of the total exergy destruction.

The performance and cost assessment of a Kalina cycle combined with Parabolic-Trough Solar Collectors using advanced exergy and exergoeconomic based approaches to detect the enhancement potential and the interaction between system components is presented [11]. Results indicate that the avoidable exergy destruction cost rate of the whole system is only 29%.

MODELING OF THE GAS TURBINE CYCLE

A simple gas turbine cycle is selected for the analysis, Figure (1). The gas cycle consists of a compressor (C), combustion chamber (C.C) and gas turbine (GT).

For the analysis, steady-state, steady flow processes are assumed. Pressure drop due to friction, heat exchange with surroundings, the change in kinetic and potential energies are neglected.

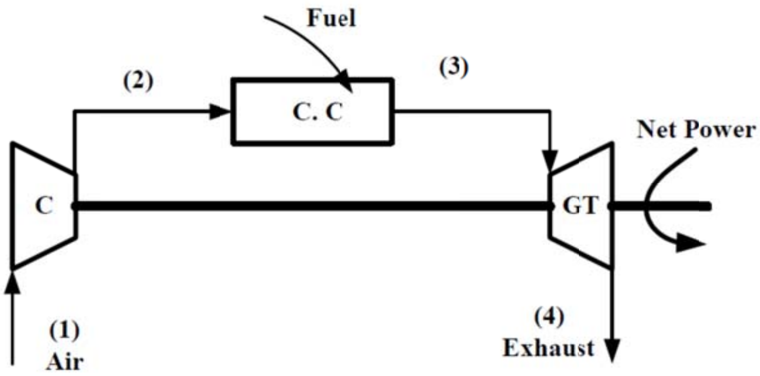


Figure 1: Simple gas turbine cycle

Conventional thermodynamic model

The first law of thermodynamics can be written as:

$$\dot{Q}_k + \sum_i (\dot{m}_i h_i)_k = \sum_e (\dot{m}_e h_e)_k + \dot{W}_k \tag{1}$$

And the first law efficiency as:

$$\eta = \frac{Energy\ sought}{Energy\ cost} \tag{2}$$

The exergy flow rate can be written as:

$$\dot{\Psi} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{3}$$

Exergy balance is given by:

$$\left(1 - \frac{T_0}{T}\right)\dot{Q}_k + \sum_i \dot{\Psi}_{i,k} = \sum_e \dot{\Psi}_{e,k} + \dot{W}_k + \dot{I}_k \tag{4}$$

By using the definitions of Fuel-Product-Loss (F-P-L) as introduced by Lozano and Valero [12]. Fuel and Product are expressed by exergy flow. Exergy balance is given as:

$$\dot{\Psi}_F = \dot{\Psi}_P + \dot{\Psi}_D + \dot{\Psi}_L \tag{5}$$

Where, $\dot{\Psi}_P$, $\dot{\Psi}_F$, $\dot{\Psi}_D and\ \dot{\Psi}_L$ are exergy rate of the desired product, exergy required (fuel) to produce it, exergy destructed during the process and exergy loss, respectively. The conventional effectiveness is given by:

$$\varepsilon = \frac{\dot{\Psi}_P}{\dot{\Psi}_F} = 1 - \frac{\dot{\Psi}_D + \dot{\Psi}_L}{\dot{\Psi}_F} \tag{6}$$

The definitions of F-P for the current power unit are given in Table (1). The conventional effectiveness of the power cycle is given as:

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times \dot{\Psi}_{fuel}} \tag{7}$$

The fuel exergy is related to the lower heating value (LHV) as [13]:

$$\frac{\psi_{fuel}}{LHV} \approx 1.06 \tag{8}$$

Table 1: F-P exergy definitions

Component	Fuel	Product
Compressor	$\dot{\Psi}_1 + \dot{W}_c$	$\dot{\Psi}_2$
Combustión Chamber	$\dot{\Psi}_{Fuel} + \dot{\Psi}_2$	$\dot{\Psi}_3$
Gas Turbine	$\dot{\Psi}_3$	$\dot{W}_{GT}$

Thermoeconomic model

In this work the specific exergy costing (SPECO) method is adopted for the analysis. In this method, the cost rates of exergy streams entering the kth component plus the cost rates associated with purchasing, maintaining and operating the same component equal to the cost rates of exergy streams leaving the component [2]. In mathematical form, the cost balance equation for a given component is be written as [2]:

$$\sum_i \left(c_i \dot{\Psi}_i\right)_k + \dot{Z}_k + c_{q,k}\dot{\Psi}_{q,k} = \sum_e \left(c_e \dot{\Psi}_e\right)_k + c_{W,k}\dot{W}_k \tag{9}$$

The annualized equipment cost is given by:

$$\dot{C}_k = (PEC)_k \times CRF \quad \left(\frac{\$}{year}\right) \tag{10}$$

Where $(PEC)_k$ is the equipment purchasing cost and CRF is the capital recovery factor given by:

$$CRF = \frac{i}{1-(1+i)^{-n}} \tag{11}$$

Here n is the life time of the equipment in years and i is the effective interest rate, given

The capital cost rate can be written as:

$$\dot{Z}_k = \frac{\emptyset_k \times \dot{C}_k}{N} \quad \left(\frac{\$}{hr}\right) \tag{12}$$

The factor ϕ_k =1.06, takes into account the maintenance cost. N is the operating time of the equipment in hours per year. To obtain the unit exergy cost for each exergy stream, a number of equations equal to the number of streams must be formulated and solved simultaneously. Since the number of streams is larger than the plant's components, a set of auxiliary equations must be formulated based on the F-P rules [12], such that the total number of equations equal to the number of unknowns.

The Specific Exergy Costing (SPECO) technique is applied for each component, the specific exergy cost is defined as:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{\Psi}_{F,k}} \tag{13}$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{\Psi}_{P,k}} \tag{14}$$

Here, $\dot{C}$ is the stream cost rate in (\$/h), $\dot{\Psi}$ in kW, and hence, the specific exergy cost "c" is in \$/kWh. The set of equations is formulated as follows:

<u>Compressor</u>

$$c_1\dot{\Psi}_1 + c_w\dot{W}_c + \dot{Z}_c = c_2\dot{\Psi}_2 \quad (15)$$

Combustion Chamber

$$c_f\dot{\Psi}_{fuel} + c_2\dot{\Psi}_2 + \dot{Z}_{c.c} = c_3\dot{\Psi}_3 \quad (16)$$

Gas Turbine

$$c3\dot{\Psi}3 + \dot{Z}_{gt} = c_W\dot{W}_{gt} + c_4\dot{\Psi}_4 \quad (17)$$

One auxiliary equation is required, which is:

$$c_4 = c_3 \quad (18)$$

Now there are four equations with four unknowns, c_2, c_3, c_4 and c_w and can be solved simultaneously for the unknowns.

The conventional exergoeconomic factor f_k designates the impact of investment cost on the total cost associated with the k^{th} component, and defined as:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} = \frac{1}{1 + \left(\frac{\dot{C}_{D,k}}{\dot{Z}_k}\right)}; \qquad 0.0 \le f_k \le 1.0 \quad (19)$$

The Purchase cost function of each piece of equipment in the gas turbine is given as [14]:

$$PEC_{ac} = \left[\frac{71.1\dot{m}_a}{0.90 - \eta_{ac}}\right]\left[\frac{P_2}{P_1}\right] ln\left[\frac{P_2}{P_1}\right] \quad (20)$$

$$PEC_{CC} = \left[\frac{46.08\dot{m}_a}{0.995 - {P_3}/{P_2}}\right]\left[1 + e^{(0.018T_3 - 26.4)}\right] \quad (21)$$

$$PEC_{gt} = \left[\frac{479.34\dot{m}_g}{0.92 - \eta_{1st}}\right] ln\left[\frac{P_3}{P_4}\right]\left[1 + e^{(0.036T_3 - 54.4)}\right] \quad (22)$$

Advanced thermodynamic model

Only part of the exergy destruction can be avoided, the rest cannot be avoided due to economic issues and technological limit, and hence, exergy destruction can be split into avoidable exergy destruction and unavoidable exergy destruction.

For a component "k" the total exergy destruction is split as:

$$\dot{\Psi}_{D,k} = \dot{\Psi}_{D,k}^{AV} + \dot{\Psi}_{D,k}^{UN} \quad (23)$$

Based on this approach, a modified effectiveness is introduced as:

$$\varepsilon_k^* = \frac{\dot{\Psi}_{P,k}}{\dot{\Psi}_{F,k} - \dot{\Psi}_{D,k}^{UN}} = \frac{\left(\dot{\Psi}_{F,k} - \dot{\Psi}_{D,k}^{UN}\right) - \dot{\Psi}_{D,k}^{AV}}{\left(\dot{\Psi}_{F,k} - \dot{\Psi}_{D,k}^{UN}\right)} = 1 - \frac{\dot{\Psi}_{D,k}^{AV}}{\dot{\Psi}_{F,k} - \dot{\Psi}_{D,k}^{UN}} \quad (24a)$$

Then from equation (23) we may have:

$$\varepsilon_k^* = 1 - \left(\frac{\dot{\Psi}_{D,k} - \dot{\Psi}_{D,k}^{UN}}{\dot{\Psi}_{F,k} - \dot{\Psi}_{D,k}^{UN}}\right) \quad (24b)$$

Equation (24b) indicates that the modified effectiveness reduces to the conventional one as the unavoidable exergy destruction becomes zero, also indicates that, the modified effectiveness increases over the conventional one with the increase in the unavoidable exergy destruction.

Due to economic and technological issues, the most efficient equipment in the market offered by manufactures is still have some exergy destruction referred as unavoidable exergy destruction, for such component the unit exergy destruction is given as: $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_P}\right)_k^{UN}$, this is the specified unavoidable exergy destruction per unit product of the component "k".

In another hand, the most inefficient component is still cost some to purchase it, the unavoided specific cost is given as: $\left(\frac{\dot{Z}}{\dot{\Psi}_P}\right)_k^{UN}$ this is the specified unavoidable purchasing cost per unit product of the component. The estimated relationship between exergy destruction is shown in Figure (2) [4].

In most cases, the considered installed equipment is neither the most expansive and efficient nor the most cheap and inefficient one. Rather than that, the operating (or design) point of the equipment under consideration is at state "A", as shown in Figure (2). In this case, the specific unavoidable exergy destruction for the state "A" is $\frac{\dot{\Psi}_{D,k,A}^{UN}}{\dot{\Psi}_{P,k,A}}$ and the unavoidable specific investment cost is $\frac{\dot{Z}_{k,A}^{UN}}{\dot{\Psi}_{P,k,A}}$.

Upon estimating the terms $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_P}\right)_k^{UN}$ and $\left(\frac{\dot{Z}}{\dot{\Psi}_P}\right)_k^{UN}$, the unavoidable exergy destruction rate $\dot{\Psi}_{D,k,A}^{UN}$ and the cost rates associated with the unavoidable exergy destruction $\dot{C}_{D,k,A}^{UN}$ and the unavoidable investment cost $\dot{Z}_{k,A}^{UN}$ at a given design state (state A), are obtained from the following relations [4]:

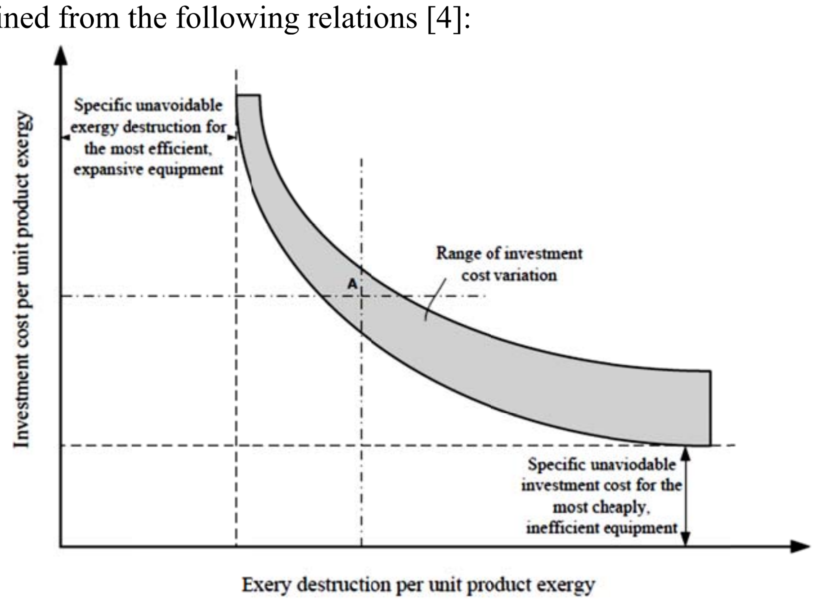


Figure 2: The estimated relationship between exergy destruction and investment cost

$$\dot{\Psi}_{D,k,A}^{UN} = \dot{\Psi}_{P,k,A}\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_p}\right)_k^{UN} \tag{25}$$

$$\dot{C}_{D,k,A}^{UN} = c_{f,,k}\dot{\Psi}_{D,k,A}^{UN} \tag{26}$$

$$\dot{Z}_{k,A}^{UN} = \dot{\Psi}_{p,k,A}\left(\frac{\dot{Z}}{\dot{\Psi}_p}\right)_k^{UN} \tag{27}$$

The avoidable terms are calculated as follows [4]:

$$\dot{\Psi}_{D,k,A}^{AV} = \dot{\Psi}_{D,k,A} - \dot{\Psi}_{D,k,A}^{UN} \tag{28}$$

$$\dot{C}_{D,k,A}^{AV} = \dot{C}_{D,k,A} - \dot{C}_{D,k,A}^{UN} \tag{29a}$$

Or

$$\dot{C}_{D,k,A}^{AV} = c_{F,,k}\dot{\Psi}_{D,k,A}^{AV} \tag{29b}$$

And

$$\dot{Z}_{k,A}^{AV} = \dot{Z}_{k,A} - \dot{Z}_{k,A}^{UN} \tag{30}$$

The modified exergoeconomic factor f_k^* designates the impact of avoidable investment cost on the total avoidable cost associated with the k[th] component, and defined as:

$$f_k^* = \frac{\dot{Z}_k^{AV}}{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}} = \frac{1}{1 + \left(\frac{\dot{C}_{D,k}^{AV}}{\dot{Z}_k^{AV}}\right)}; \quad 0.0 \leq f_k^* \leq 1.0 \tag{31}$$

INPUT DATA

For the analysis the specific cost of the inlet air, $c_1 = 0.00 \ \$/kWh$, and the specific cost of the fuel (gas) entering the combustion chamber, $c_f = 0.011052 \ \$/kWh$. Other input data for the analysis is given in Table (2) [15].

Table 2: Input data

T_1 (K)	P_1 (kPa)	T_3 (K)	P_4 (kPa)	r_p	η_{gt}	η_{cc}	η_c
288.15	101.3	1515	101.3	17.5	0.85	0.90	0.80
T_0 (K)	P_0 (kPa)	T_f(K)	$\dot{m}_a$(kg/s)	LHV (kJ/kg)	i	N (y)	
298.15	101.3	288.1	672	50030	0.18	25	

RESULTS AND DISCUSSIONS

The results may be classified into conventional and advanced thermoeconomic results.

Results of the conventional thermoeconomic model

Table (3) shows the temperature, pressure, mass flow rate and exergy for each stream.

Table 3: The thermodynamic findings for each stream

State	T (K)	P (kPa)	$\dot{m}(\frac{kg}{s})$	$\psi\ (\frac{kJ}{kg})$	$\dot{\Psi}\ (kW)$
1	288.15	101.3	672	0.1522	102.2784
2	720.7	1772.75	672	416.4	279820.8
3	1515	1742.75	690.39	1151	794638.9
4	891.3	101.3	690.39	309.2	213468.6

It is found that, the rate of heat added in the combustion chamber is 920 MW, the turbine power output is 547.3 MW, and the compressor input power is 306.7 MW, hence the net power output is 240.6 MW and the thermal efficiency is 26.15%

Thermoeconomic analysis reveals the specific cost for each stream; the results are tabulated in Table (4). The results are in the range with that given in the literature [16].

Table 4: The specific cost

	\$/kwh	\$/GJ
c_1	0	0
c_2	0.0310	8.6257
c_3	0.0235	6.5260
c_4	0.0235	6.5261
c_w	0.02631	7.3094

The results of cost rate are shown in Table (5). The exergy destruction, the effectiveness, the cost rate of the exergy destruction and hence the total cost rate are the largest for the combustion chamber, the result is in the order of magnitude with that given in the literature [17], [7].

Table 5: The cost rate of the design case

Comp.	$\dot{\Psi}_p(kW)$	$\dot{\Psi}_{D,k}(kW)$	$c_{f,k}\ (\frac{\$}{kWh})$	$\dot{Z}_k\ (\frac{\$}{h})$	$\dot{C}_{D,k}\ (\frac{\$}{h})$	$\dot{Z}_k + \dot{C}_{D,k}\ (\frac{\$}{h})$
AC	279820	26981	0.0263	618.70	710	1328.70
CC	794639	460437	0.0147	227.41	6766	6993.41
GT	547300	33870	0.0235	747.72	795.74	1543.46

Results of the advanced thermoeconomic model

For the compressor, equation (20) indicates that the purchased cost of the compressor turns into infinite when its isentropic efficiency is 90%. This efficiency is considered as the best one in the market, the exergy destruction associated with it, is unavoidable, the product exergy at this efficiency is also calculated. Hence, we find, $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_p}\right)_{comp}^{UN} = 0.0478$. Then for the design case (state A, see Figure (2)), from equation (25) and Table (5), we get

$$\dot{\Psi}_{D,comp}^{Un} = 279820 \times 0.0478 = 13375.396\ kW$$

Also from equation (28) and Table (5), we get

$$\dot{\Psi}_{D,comp}^{AV} = 26981 - 13375.396 = 13605.604\ kW$$

The rate of the unavoidable exergy destruction cost is calculated as (Equation (26) and Table (5)),

$$\dot{C}_{D,k}^{UN}\left(\frac{\$}{h}\right) = 0.0263 \times 13375.396 = 351.77\ \$/h$$

The rate of the avoidable exergy destruction cost is calculated as (Equation (29) and Table (5)),

$$\dot{C}_{D,comp}^{AV} = 710 - 351.77 = 358.23\ \$/h$$

The specific investment cost, $\left(\frac{\dot{\mathrm{Z}}}{\dot{\Psi}_{\mathrm{p}}}\right)_{\mathrm{comp}}^{\mathrm{UN}} = 0.00018\$/\mathrm{kWh}$, is calculated from equation (20), by taking an isentropic efficiency of 50%, (this efficiency is assumed for the most inefficient compressor offered by the manufacturers).

Then for the design case (state A) we obtain from equation (27) and Table (5) the unavoidable cost rate

$$\dot{Z}^{UN}_{comp} = 0.00018 \times 279820 = 50.37\ {}^{\$}/_{h}.$$

Then the avoidable cost rate is calculated from equation (30) and Table (5) as

$$\dot{Z}^{AV}_{comp} = 618.7 - 50.37 = 567.33\ {}^{\$}/_{h}$$

Results are tabulated in Table (6).

For the gas turbine, equation (22) shows that the purchased cost of the gas turbine turns into infinite when its isentropic efficiency is 92%. Using this value we may find: $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_p}\right)^{UN}_{gt} = 0.0323.$

Then for the design case (state A), from equation (25) and Table (5), we get:

$$\dot{\Psi}^{Un}_{D,gt} = 0.0323 \times 547300 = 17677.79 \text{ kW}.$$

Also from equation (28) and Table (5), we get

$$\dot{\Psi}^{AV}_{D,gt} = 33870 - 17677.79 = 16192.21 \text{ kW}$$

The rate of the unavoidable exergy destruction cost is calculated as (Equation (26) and Table (5)),

$$\dot{C}^{UN}_{D,gt} = 0.0235 \times 17677.79 = 415.43\ \$/h$$

The rate of the avoidable exergy destruction cost is calculated as (Equation (29) and Table (5)),

$$\dot{C}^{AV}_{D,gt} = 795.74 - 415.43 = 380.31\ \$/h$$

The specific investment cost $\left(\frac{\dot{Z}}{\dot{\Psi}_p}\right)^{UN}_{gt}$ is calculated from the cost equation (22) and an isentropic efficiency of 65% as 0.00022 \$/kWh, (65% efficiency is assumed for the most inefficient gas turbine offered by the manufacturers).

Then for the design point (state A) we obtain by using equation (27) and Table (5) the unavoidable cost rate:

$$\dot{Z}^{UN}_{gt} = 0.00022 \times 547300 = 120.41\ {}^{\$}/_{h}$$

Then the avoidable cost rate is calculated from equation (30) and Table (5),

$$\dot{Z}^{AV}_{gt} = 747.72 - 12.41 = 627.31\ {}^{\$}/_{h}$$

Results are tabulated in Table (6).

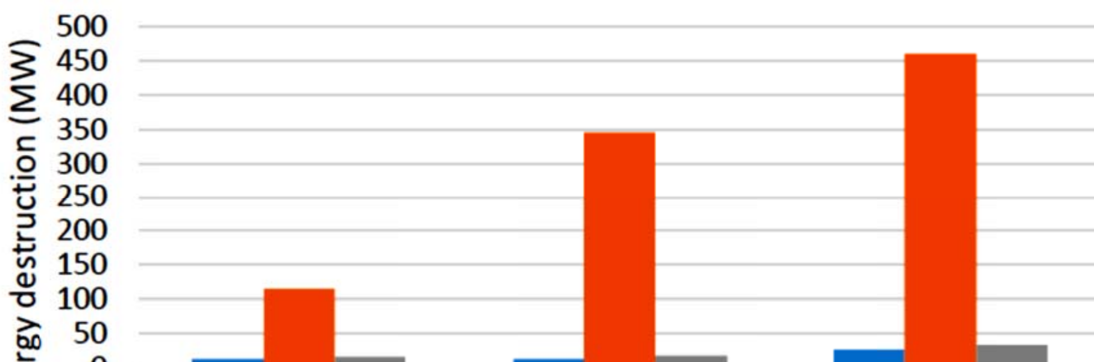
For the combustion chamber, the ratio $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_p}\right)^{UN}_{cc}$ is estimated by assuming high temperatures of the reactants (811 K for fuel and 1000 K for air), a high outlet temperature (1773 K), and adiabatic combustion [4]. With the aid of the cost function (equation (21)) we calculate: $\left(\frac{\dot{\Psi}_D}{\dot{\Psi}_p}\right)_{cc}^{UN} = 0.4343$.

To estimate the ratio $\left(\frac{\dot{Z}}{\dot{\Psi}_p}\right)_{cc}^{UN}$ we assume ambient temperatures at the inlet, ambient pressure in the combustion chamber, and a low temperature at the outlet (1273 K) [4], then we calculate with the aid of the cost function: $\left(\frac{\dot{Z}}{\dot{\Psi}_p}\right)_{cc}^{UN} = 3.3 \times 10^{-6}\ \$/_{kWh}$. The remaining variables are calculated as in the previous two components and presented in Table (6).

Table 6: Results of cost rate of the advanced model

	$\dot{\Psi}_{D,k}^{UN}\ (kW)$	$\dot{\Psi}_{D,k}^{AV}\ (kW)$	$\dot{C}_{D,k}^{UN}\ (\frac{\$}{h})$	$\dot{C}_{D,k}^{AV}\ (\frac{\$}{h})$	$\dot{Z}_{k}^{UN}\ (\frac{\$}{h})$	$\dot{Z}_{k}^{AV}\ \left(\frac{\$}{h}\right)$
AC	13375.396	13605.604	351.77	358.23	50.37	567.33
CC	345113	115323	5071	1695	2.49	224.92
GT	17677.79	16192.21	415.43	380.31	120.41	627.31

Figure (3) summarizes the exergy destruction for the three components, as can be seen the exergy destruction is split into avoidable and unavoidable parts, and the maximum exergy destruction occurs in the combustion chamber with total exergy destruction of 460 MW. Due to high irreversibility in the combustion chamber, the unavoidable exergy destruction attains much higher value than the avoidable one, the result is in a good agreement with that given in the literature [7]



	Avoidable	Unavoidable	Total
AC	13.6	13.4	27
CC	115	345	460
GT	16.2	17.7	33.9

Figure 3: Exergy destruction (MW)

The cost rates for the exergy destruction of the three components are summarized in Figure (4). As can be seen, the cost rates are split into avoidable and unavoidable parts. Due to large irreversibility, the cost rate of the unavoidable exergy destruction of the combustion chamber is large compared to the compressor and gas turbine, the result is in a good agreement with that given in the literature [8].

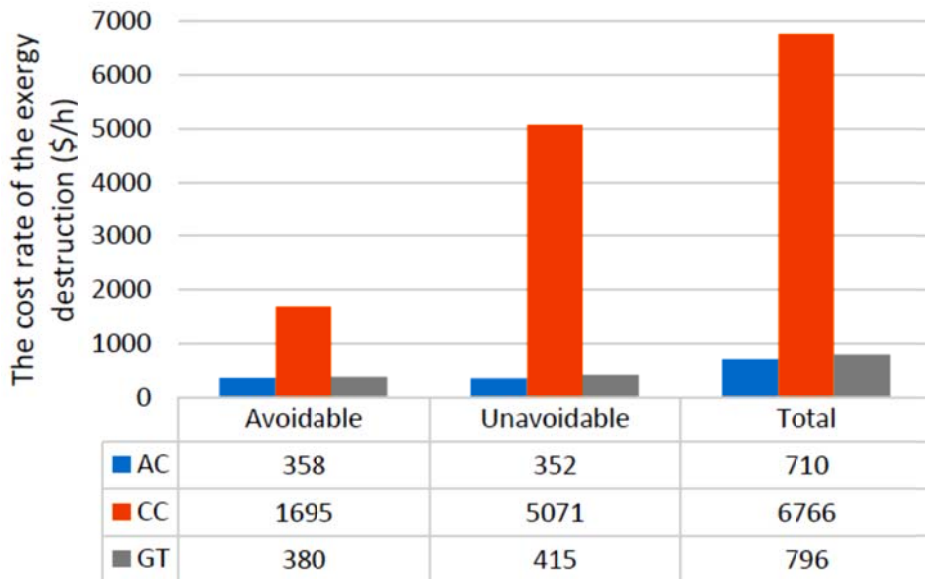


Figure 4: The cost rate of the Exergy Destruction ($/h)

The rates of the investment cost are shown in Figure (5). The avoidable parts of the investment cost rate are dominant for the three components, specifically for the combustion chamber. The avoidable part could be reduced be selecting more efficient components

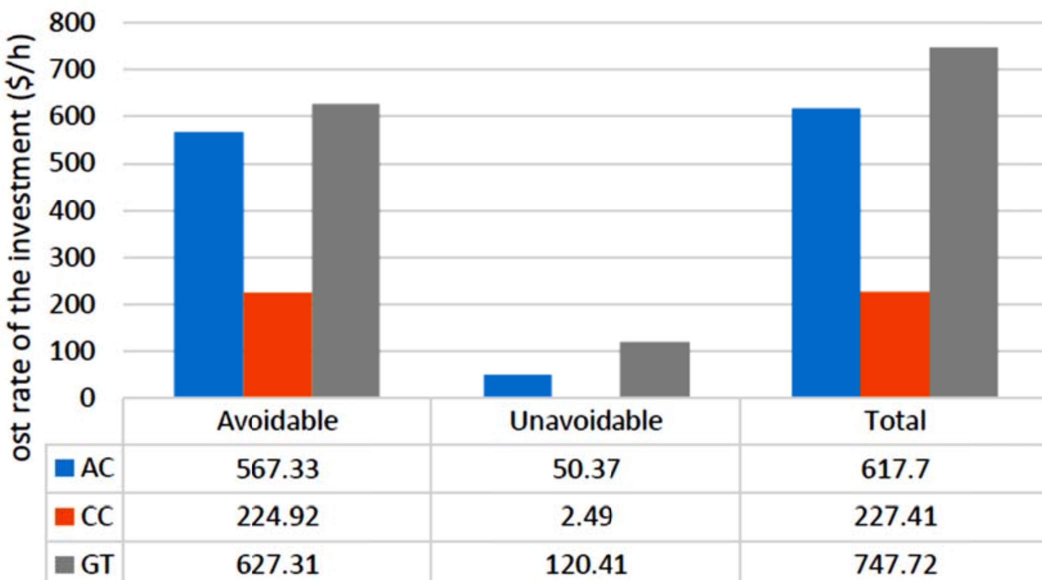
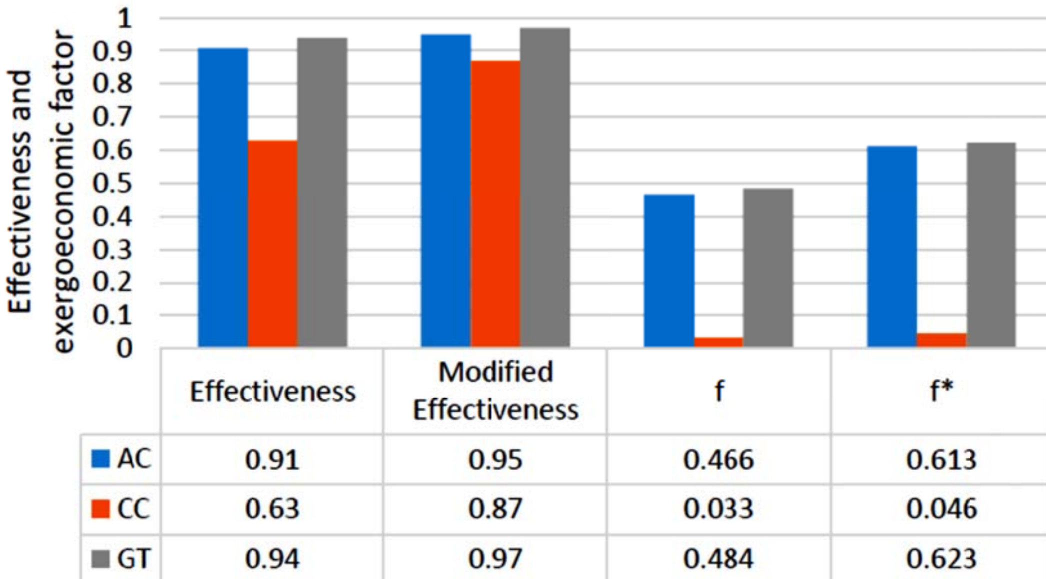


Figure 5: The cost rate of the investment ($/h)

The conventional and modified effectiveness are shown in Figure (6). The discrepancy between them is due to considering the unavoidable part of the exergy destruction when calculating the modified effectiveness as indicated by Equation (24b). The discrepancy increases with the increase in the unavoidable part of the exergy destruction.

The exergoeconomic factor "f" specifies the impact of the investment cost on the total cost of the specified component, while the modified exergoeconomic cost "f*" specifies the impact of the avoidable investment cost on the avoidable total investment cost for the same component.

Exergoeconomic factors are calculated and plotted in Figure (6). Large value of exergoeconomic factor (approaches unity), designates large investment cost and/or low cost rate of the exergy destruction. Large values indicate the need for reducing the investment cost. Low value of the exergoeconomic factor (approaches zero), points to low investment cost and/or large cost rate of the exergy destruction. Low values, specifies the need for reducing the cost rate of the exergy destruction.



	Effectiveness	Modified Effectiveness	f	f*
AC	0.91	0.95	0.466	0.613
CC	0.63	0.87	0.033	0.046
GT	0.94	0.97	0.484	0.623

Figure 6: Effectiveness and exergoeconomic factor

For the combustion chamber, both factors show extremely low values due to high exergy destruction and high cost rate of the exergy destruction. However, for the gas turbine and compressor, the modified exergoeconomic factors show higher values than the conventional exergoeconomic factors. In this particular case, the factor f^* emphasizes on more attention should be paid to reduce the investment costs than the factor f.

For the whole plant the conventional effectiveness is calculated as 24.67%, while the modified effectiveness calculated as 40.14%. Also, the conventional exergoeconomic factor is calculated as 16.15% while the modified factor calculated as 36.85%. The discrepancy emphasizes the advantages of such approach to give a rational judgment of the performance of thermal systems.

CONCLUSIONS

A simple gas turbine cycle is analyzed by splitting the exergy destruction into avoidable and unavoidable parts; the results are compared with the conventional thermoeconomic approach. The following conclusions are drawn:

- The modified exergoeconomic factor is more realistic, rational and helps the designer in making the right decisions in cost minimization process of the whole plant.
- The modified effectiveness offers more realistic picture to the designer for improving the thermodynamic performance of the component under

consideration. It may be used to compare the performance of dissimilar components when the specific unavoidable exergy destruction is evaluated rationally.

NOMENCLATURE

f	exergoeconomic factor	subscript	
h	enthalpy [kJ/kg]	a	air
$\dot{I}$	irreversibility rate [kW]	A	design state
$\dot{m}$	mass flow rate [kg/s]	c	compressor
$\dot{Q}$	heat transfer rate [kW]	cc	combustion chamber
rp	pressure ratio	D	destruction
s	entropy [kJ/kg.K]	e	exit
T	temperature [^{o}C]	F	fuel
$\dot{W}$	power [kW]	g	gas
Greek		gt	gas turbine
η	efficiency	i	inlet
ε	effectiveness	k	component
$\dot{\Psi}$	exergy rate [kW]	L	loss
superscript		o	ambient
AV	avoidable	P	product
UN	unavoidable	w	work

REFERENCES

[1] G. Fellah, "Thermoeconomic analysis of a single effect, mechanical vapor compression desalination unit," *i-manager's J. Mech. Eng.*, vol. 9, no. 3, pp. 1–8, 2019.

[2] H. Elhejaji and G. Fellah, "Thermoeconomic analysis of alkhoms steam power plant at different operating loads," *J. Eng. Res. (University Tripoli)*, vol. 1, no. 31, pp. 71–83, 2021.

[3] G. D. Vŭković, M. V. Vukić, M. M. Stojiljkovića, and D. D. Vŭković, "Avoidable and unavoidable exergy destruction and exergoeconomic evaluation of the thermal processes in a real industrial plant," *Therm. Sci.*, vol. 16, no. SUPPL.2, 2013.

[4] G. Tsatsaronis and M. H. Park, "On avoidable and unavoidable exergy destructions and investment costs in thermal systems," *Energy Convers. Manag.*, vol. 43, no. 9–12, pp. 1259–1270, 2002.

[5] P. Gullo, G. Cortella, and S. Minetto, "Potential enhancement investigation of commercial R744 refrigeration systems based on avoidable and unavoidable exergy destruction concepts," *Refrig. Sci. Technol.*, no. August, pp. 277–284, 2016.

[6] E. Bozoglan, Z. Erbay, A. Hepbasli, and H. Gunerhan, "Splitting the exergy destructions of an olive oil refining plant into avoidable and unavoidable parts based on actual operational data," *Int. J. Exergy*, vol. 21, no. 3, pp. 277–294, 2016.

[7] F. Petrakopoulou, G. Tsatsaronis, T. Morosuk, and A. Carassai, "Conventional

and advanced exergetic analyses applied to a combined cycle power plant," *Energy*, vol. 41, no. 1, pp. 146–152, 2012.

[8] C. Uysal, "A new approach to advanced exergoeconomic analysis: The unit cost of entropy generation," *Environ. Prog. Sustain. Energy*, vol. 39, no. 1, pp. 1–15, 2020.

[9] V. Ambriz and C. Rubio-maya, "Avoidable and Unavoidable Exergy Analysis for a Cascade Geothermal Plant Producing ... Avoidable and Unavoidable Exergy Analysis for a Cascade Geothermal Plant Producing Electricity , Cooling and," in *ECRES – 5th European Conference on Renewable Energy Systems, Sarajevo, Bosnia and Herzegovina*, 2017, no. August, pp. 1–6.

[10] O. Balli, "Advanced Exergy Analysis of a Turbofan Engine (TFE): Splitting Exergy Destruction into Unavoidable/Avoidable and Endogenous/Exogenous," *Int. J. Turbo Jet Engines*, vol. 36, no. 3, pp. 305–327, 2019.

[11] F. A. Boyaghchi and M. Sabaghian, "Advanced exergy and exergoeconomic analyses of Kalina cycle integrated with parabolic-trough solar collectors," *Sci. Iran.*, vol. 23, no. 5, pp. 2247–2260, 2016.

[12] M. A. Lozano and A. Valero, "Theory_of_exergetic_cost," *Energy*, vol. 18, no. 9, pp. 939–960, 1993.

[13] J. Kenneth Wark, *Advanced Thermodynamics for Engineers*. 1995.

[14] M. Ameri and N. Enadi, "Thermodynamic modeling and second law based performance analysis of a gas turbine power plant (exergy and exergoeconomic analysis)," *J. Power Technol.*, vol. 92, no. 3, pp. 183–191, 2012.

[15] I. A. Elfeituri, "Thermodynamic performance of a 285 MW gas turbine unit under varying operating conditions," *J. Eng. Res. (University Tripoli, Libya)*, no. March 2017, pp. 145–162, 2017.

[16] S. O. Oyedepo, R. O. Fagbenle, S. S. Adefila, and M. M. Alam, "Exergoeconomic analysis and performance assessment of selected gas turbine power plants," *World J. Eng.*, vol. 12, no. 3, pp. 283–300, 2015.

[17] A. Mousafarash and M. Ameri, "Exergy and exergo-economic based analyses of a gas turbine power generation system," *J. Power Technol.*, vol. 93, no. 1, pp. 44–51, 2013.