EXERGOECONOMIC AND EXERGOENVIRONMENTAL ANALYSES: A RATIONAL APPROACH FOR ASSESSING THE PERFORMANCE OF A 47 MW GAS TURBINE POWER UNIT

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Received 23 July 2025; Revised 25 August 2025; Accepted 27 September 2025; Published 10 November 2025

الملخص

أجري تحليل إكسيرجو-اقتصادي وإكسيرجو-بيئي معمق على وحدة توربين غازي بقدرة تشغيلية مقدارها 30.5 ميغاواط وسعة اسمية قدرها 47 ميغاواط. وقد أظهرت النتائج أن الكفاءة الإكسيرجية منخفضة نسبيًا، ويُعزى ذلك بشكل رئيس إلى معدلات التدمير العالية للإكسيرجي في غرفة الاحتراق. تناول التقييم الأكسيرجو-اقتصادي ثلاثة سيناريوهات لأسعار الوقود، حيث تبيّن أنه عند انعدام تكلفة الوقود يصل العامل الأكسيرجو-اقتصادي إلى 100%، مما يعني أن تكاليف رأس المال تشكل المساهمة الرئيسة. أما التقييم الإكسيرجو-بيئي فقد شمل تقدير معدلات الأثر البيئي المرتبطة بدورات حياة المكوّنات، وتدمير الإكسيرجي، ومؤشرات الفروق النسبية، إلى جانب العامل الإكسيرجو-بيئي. بلغ إجمالي الأثر البيئي لوحدة التوربين الغازي بالكامل 1,124,328 مللي نقطة / ساعة، بينما سجّلت غرفة الاحتراق أعلى معدل للأثر البيئي بلغ 857,895 مللي نقطة / ساعة بنسبة 76.30%. كانت الآثار البيئية الكلية المرتبطة بعمليات التصنيع والتشغيل والصيانة والتخلص من المكوّنات الرئيسة محدودة نسبيًا. وتؤكد هذه النتائج ضرورة تحسين تصميم منظومة الاحتراق بهدف رفع الكفاءة والحد من التكاليف الاقتصادية والبيئية.

ABSTRACT

An in-depth exergoeconomic and exergoenvironmental analysis was performed on a 30.5 MW gas turbine power unit with a nominal capacity of 47 MW. The exergetic efficiency was found to be relatively low, mainly due to substantial exergy destruction in the combustion chamber. The exergoeconomic evaluation considered three fuel price scenarios, revealing that at zero fuel cost, the exergoeconomic factor reached 100%, indicating capital costs as the dominant contributor. The exergoenvironmental assessment included the estimation of environmental impact rates related to component life cycles, exergy destruction, relative difference indicators, and the exergoenvironmental factor.

The total environmental impact of the gas turbine unit was determined to be 1,124,328 mPts/h. Among the components, the combustion chamber accounted for the largest share, contributing 857,895 mPts/h, which corresponds to 76.30% of the overall environmental impact. However, the overall environmental impacts associated with production, operation, maintenance, and disposal of the main components were comparatively minor. These results highlight the need for improving combustion system design to enhance efficiency and reduce both economic and environmental costs.

KEYWORDS: Exergy, Exergoeconomic, Specific exergy costing, Exergoenvironmental, Life cycle assessment, Environmental impact, Eco-99 indicator.

INTRODUCTION

Due to the finite nature of natural resources and growing global energy demands, energy experts are working diligently to develop rational, efficient, cost-effective, and environmentally friendly thermal systems. Linking exergy with economic and environmental principles provides a systematic approach to analyze and optimize these systems [1].

Exergy, exergoeconomic, and exergoenvironmental analyses are employed to evaluate the performance of thermal systems from thermodynamic, economic, and environmental perspectives. Exergy analysis identifies exergy destruction (irreversibility) within each component of a thermal system, thereby assessing its thermodynamic performance. In exergoeconomic analysis, costs are assigned to exergy streams to calculate the cost associated with exergy destruction. For environmental impact assessment, the life cycle of the system's components must be considered, from raw material extraction and manufacturing to operation and final disposal. A key method in exergoeconomic, known as **S**pecific **E**xergy **C**osting (**SPECO),** has been developed to establish the theoretical foundations for various applications of exergetic cost. In addition, it provides the fundamental concepts and principles necessary for describing formation processes and evaluating efficiency in energy systems. [2].

In recent years, considerable research has focused on evaluating thermal systems from a thermoeconomic perspective. Within this context, the application of exergoeconomic analysis has been investigated as a means to assess the performance of a complete charging–discharging cycle in sensible heat thermal energy storage system [3]. The primary objective of such studies is to optimize the storage unit's performance while minimizing the total cost of ownership and operation. A cogeneration thermal system comprising a combined gas turbine and organic Rankine cycle has been analyzed, aiming to optimize design parameters from both thermodynamic and economic viewpoints [4].

Comprehensive exergoeconomic modeling of gas turbine power plants in Iran was also conducted, with MATLAB software used to simulate processes and evaluate thermodynamic and exergoeconomic performance [5]. Exergetic cost analysis was adopted to determine both monetary and exergetic costs and to improve the performance of the power generation system at Companhia Siderúrgica Tubarão in Brazil [6]. The plant operates based on a regenerative Rankine cycle, utilizing two gas streams, blast furnace gas and coke oven gas, to generate electricity and steam for industrial processes.

A systematic analysis of Unit GT14 at the South Tripoli (Libya) gas turbine power plant was conducted using exergetic and economic assessments based on the SPECO method. The results revealed that the combustion chamber accounted for the highest share of exergy destruction cost, exerting the most significant influence on the overall cost of exergy destruction [7].

Exergoenvironmental analysis has been conducted by linking the life cycle of a system's components, their associated environmental impacts, and exergy. The primary objective is to determine the environmental impact, expressed in points per unit of exergy, for each stream and for the exergy destruction occurring within each system component. In this context, the exergoeconomic and exergoenvironmental simulation of a co-generative power plant, comprising a gas/steam turbine power plant integrated with a solar field, was performed. The simulation, designed to produce approximately 400 MW of electrical power, aimed to evaluate the environmental impact of the solar collector components. Based on the findings, it was recommended to increase the condenser's capital cost and efficiency in order to reduce its overall environmental impact [8].

An exergoeconomic and exergoenvironmental evaluation of two large combined heat and power (CHP) geothermal power plants was conducted. The objective was to determine the cost and environmental impact associated with producing electricity and heat. Additionally, the build-up of the economic and environmental impacts was analyzed, allowing for the identification of the most critical components. Based on this analysis, suggestions for improving system performance were provided [9].

As a case study, an advanced exergoenvironmental analysis of a geothermal power plant was performed. The environmental impacts of each component, along with exergy degradation and pollution formation, were separated into endogenous/exogenous and avoidable/unavoidable parts. The analysis revealed that the environmental impact was mostly caused by exergy destruction [10].

Exergy, exergoeconomic and exergoenvironmental valuations of experimental hybrid energy systems for hot water production was presented [11]. An experimental rig was developed to test and control different system configurations for hot water supply in buildings. Three different scenarios were studied: a combined boiler–cogeneration system, a combined boiler–solar collector system, and a combined boiler–heat pump system. It was concluded that the production of domestic hot water using the combined boiler–solar thermal collector system was the most appropriate scenario from both economic and environmental perspectives.

Exergetic parameters for steam power plant components were developed to assess the environmental impact of these components during their operation. In addition to exergetic efficiency, other parameters were introduced for the analysis [12], including the exergy destruction factor, environmental destruction coefficient, environmental destruction index, and environmental benign index. The values obtained were significant, particularly when comparative evaluations were conducted to assess the environmental impact of the different components.

The motivation for the present study stems from the need to assess the environmental impact of power generation facilities, as the conversion of fuel energy into electricity inherently affects the environment. Inefficient operation of these plants further exacerbates pollution and poses risks to human health. In this context, exergy, exergoeconomic, and exergoenvironmental analyses are carried out for the Al-Zahra gas turbine unit. These analyses are conducted under various fuel cost scenarios to capture a broad range of operational conditions. The power plant is located in Al-Zahra City, in the northwestern region of Libya, at approximately 32.679847° N latitude and 12.878595° E longitude.

MATERIALS AND METHODS

In this study, a single unit with operating capacity of 30.5 MW (nominal capacity of 47 MW) is selected as a case study to investigate the exergoeconomic and exergoenvironmental methodologies for assessing the specific cost and **E**nvironmental **I**mpact (**EI**) associated with the ownership and operation of gas turbine power plants. The configuration of the power unit is shown in Figure (1), it consists of an **A**ir **C**ompressor (**AC**), **C**ombustion **C**hamber (**CC**) and **G**as **T**urbine (**GT**). Air enters the compressor at a temperature of 298.15 K and a pressure of 101.325 kPa. The compressor's pressure ratio is 10, with an isentropic efficiency of 84%. The gas turbine inlet temperature is 1425.15 K, which has an isentropic efficiency of 85%. The operating data for the gas turbine unit is presented in Table (1).

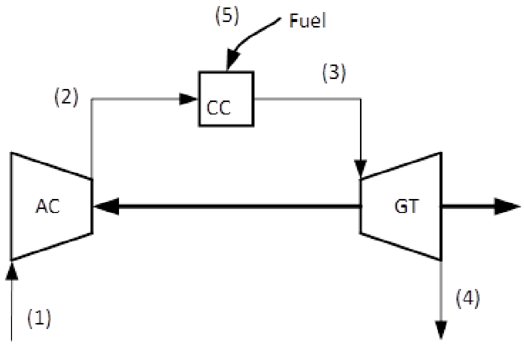


Figure 1: The gas turbine power unit.

Table 1: The operating data for the gas turbine power unit.

Item	Operating parameters
Dead state	298.15 K, 101.325 kPa
Air compressor	Air inlet condition: 298.15 K, 101.325 kPa. Pressure ratio = 10, Isentropic efficiency = 84%
Gas turbine	Inlet temperature = 1425.15 K, Exit pressure = 101.325 kPa, Isentropic efficiency = 85%
Combustion chamber	Fuel is natural gas: LHV = 46669 (kJ/kg), T_f = 305.85 (K). Pressure drop = 5%.
Air mass flow rate	$\dot{m}_a = 132.05 \left(\frac{kg}{s}\right)$
Fuel mass flow rate	$\dot{m}_{\text{fuel}} = 3.34 \left(\frac{\text{kg}}{\text{s}}\right)$

The Thermodynamic Model

For steady-state, steady-flow processes, we may write for a component "k":

- The continuity equation is

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

- Neglecting the change in kinetic and potential energy, the energy balance equation is

$$\dot{Q}_k + \sum_i \dot{m}_i h_i = \dot{W}_k + \sum_e \dot{m}_e h_e \tag{2}$$

- The exergy balance equation is

$$\dot{\Psi}_{q,k} + \sum_i \dot{m}_i \psi_i = \dot{W}_k + \sum_e \dot{m}_e \psi_e + \dot{\Psi}_{D,k} \tag{3}$$

where

$$\dot{\Psi}_{q,k} = \dot{Q}_k \left(1 - \frac{T_0}{T}\right) \tag{4}$$

and

$$\psi = (h - h_0) - T_0(s - s_0) \tag{5}$$

The rate of exergy destruction is given by

$$\dot{\Psi}_D = \dot{\Psi}_F - \dot{\Psi}_p \tag{6}$$

The chemical exergy of the fuel can be found from [13] as

$$\psi_{fuel} = 1.065 \times \dot{m}_{fuel} \times LHV \ \ (kW) \tag{7}$$

For Figure (1), the forms of exergy, exergy destruction and the exergetic efficiency (ε) are presented in Table (2).

Table 2: Exergy, exergy destruction and exergetic efficiency.

Component	$\dot{\Psi}_F$	$\dot{\Psi}_P$	$\dot{\Psi}_D$	ε
Compressor	$\dot{W}_C$	$\dot{\Psi}_2 - \dot{\Psi}_1$	$\dot{W}_C - (\dot{\Psi}_2 - \dot{\Psi}_1)$	$\frac{(\dot{\Psi}_2 - \dot{\Psi}_1)}{\dot{W}_C}$
Combustion chamber	$\dot{\Psi}_{fuel}$	$\dot{\Psi}_3 - \dot{\Psi}_2$	$\dot{\Psi}_{fuel} - (\dot{\Psi}_3 - \dot{\Psi}_2)$	$\frac{(\dot{\Psi}_3 - \dot{\Psi}_2)}{\dot{\Psi}_{fuel}}$
Gas turbine	$\dot{\Psi}_3 - \dot{\Psi}_4$	$\dot{W}_T$	$(\dot{\Psi}_3 - \dot{\Psi}_4) - \dot{W}_T$	$\frac{\dot{W}_T}{(\dot{\Psi}_3 - \dot{\Psi}_4)}$

Exergoeconomic Model

Exergoeconomic (also known as thermoeconomic) is an approach that combines exergy and economic analyses to evaluate the specific cost of each stream within a cycle. Exergoeconomic analysis of a system aims to minimize the cost associated with the exergy destruction**.** A cost balance is then established for each component comprising the system to evaluate economic performance and identify areas for improvement. The approach is based on the **Sp**ecific **E**xergy **Co**sting (**SPECO**) theory [2]. The basic exergoeconomic equation is given by

$$c_F \dot{\Psi}_F + \dot{Z} = c_P \dot{\Psi}_P \tag{8}$$

The typical cost per kW for a medium-scale gas turbine power plant is approximately 550 \$/kW (Gas Turbine costs \$/KW - Gas Turbine World). The cost of 47 MW gas turbine plant is then \$25.850 million. The cost distribution among the plant's major components is generally as follows:

1. Gas Turbine: 40–50% of the total cost.
2. Compressor: 15–25% of the total cost.
3. Combustor: 5–15% of the total cost.
4. Generator: 10–20% of the total cost.
5. Balance of Plant: 10–20% of the total cost (Includes auxiliary systems such as electrical infrastructure, control units, and other support facilities).

Based on the above cost structure, the estimated costs for the main components of a 47 MW gas turbine power plant are: Z_{GT}: \$12.925 million, Z_{AC}: \$6.4625 million and Z_{CC}: \$3.8775 million. These figures align with the typical percentage ranges and serve as a reference for assessing similar scale projects. Clear understanding of these cost elements is essential for budgeting, investment planning, and feasibility studies in energy infrastructure projects. The capital investment of a component is converted into the cost rate by the following relation:

$$\dot{Z}_k = Z \times CRF \times \frac{\varphi}{N \times 3600} \left(\frac{\$}{s}\right) \tag{9}$$

where φ is the maintenance factor of 1.06, N is the number of operating hours per year taken as 7500 hours, and CRF is the capital recovery factor given by

$$\mathrm{CRF} = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} \tag{10}$$

For the analysis the time period (n) is taken as 25 years and the interest rate (i) as 7%. The cost rate equation is given by

$$\sum_i \dot{C}_{i,k} + \dot{C}_{q,k} + \dot{Z}_k = \sum_e \dot{C}_{e,k} + \dot{C}_{w,k} \tag{11}$$

Then

$$\sum_i \left(c_i \dot{\Psi}_i\right)_k + c_{q,k} \dot{\Psi}_{q,k} + \dot{Z}_k = \sum_i \left(c_e \dot{\Psi}_e\right)_k + c_{w,k} \dot{\Psi}_{w,k} \tag{12}$$

where

$$\dot{C} = c\dot{\Psi}_j \tag{13}$$

The exergoeconomic factor is given by

$$f_{ec} = \frac{\dot{Z}}{\dot{Z} + \dot{C}_D} = \frac{\dot{Z}}{\dot{Z} + c_F \dot{\Psi}_D} \tag{14}$$

The relative exergoeconomic factor is given by

$$r_{ec} = \frac{c_P - c_F}{c_F} \tag{15}$$

For the components in Figure (1), the thermoeconomic equations are written as:

For air compressor:

$$c_2 \dot{\Psi}_2 = c_1 \dot{\Psi}_1 + c_w \dot{W}_{AC} + \dot{Z}_{AC} \tag{16}$$

$$c_F = c_w \tag{17}$$

$$c_P = \frac{c_2 \dot{\Psi}_2 - c_1 \dot{\Psi}_1}{\dot{\Psi}_2 - \dot{\Psi}_1} \tag{18}$$

For combustion chamber:

$$c_3 \dot{\Psi}_3 = c_2 \dot{\Psi}_2 + c_{fuel} \dot{\Psi}_{fuel} + \dot{Z}_{CC} \tag{19}$$

$$c_F = c_{fuel} \tag{20}$$

$$c_P = \frac{c_3 \dot{\Psi}_3 - c_2 \dot{\Psi}_2}{\dot{\Psi}_3 - \dot{\Psi}_2} \tag{21}$$

For Gas turbine:

$$c_4 \dot{\Psi}_4 + c_w \dot{W}_{GT} = c_3 \dot{\Psi}_3 + \dot{Z}_{GT} \tag{22}$$

$$c_F = \frac{c_3 \dot{\Psi}_3 - c_4 \dot{\Psi}_4}{\dot{\Psi}_3 - \dot{\Psi}_4} \tag{23}$$

$$c_P = c_W \tag{24}$$

The auxiliary equations are given by:

$$c_3 = c_4 \tag{25}$$
$$c_1 = 0.0 \tag{26}$$

In Libya, natural gas is widely used for gas turbine power plants to produce electricity, mainly by the General Electricity Company of Libya (GECOL). However, determining the real price of natural gas used in these plants is challenging due to the lack of publicly accessible data on internal transfer pricing between the National Oil Corporation (NOC) and GECOL.

Remarkably, as of December 2024, the stated price of natural gas for both households and businesses in Libya was $0.000 per kWh, indicating that natural gas is heavily subsidized or provided at no cost to end-users (Libya natural gas prices, December 2024 | GlobalPetrolPrices.com). Given this background, it is reasonable to deduce that the price of natural gas for electricity generation in Libya is negligible or effectively zero, due to government subsidies.

This subsidization contributes to the country's low electricity prices. For comparison, the price of natural gas in the world in that month is 0.078 U.S. Dollar per kWh for households and 0.066 U.S. Dollar per kWh for businesses. These rates include all taxes, fees and other components of the gas bill (https://www.globalpetrolprices.com/Libya/natural_gas_prices/). However, these prices are subject to market fluctuations and regional differences. In some instances, the cost of natural gas has been reported as high as $1.61 per kg (124.194 $/MWh) [14].

Life Cycle Assessment

Life **C**ycle **A**ssessment (**LCA**) is an approach used to evaluate the **E**nvironmental **I**mpact (**EI**) of a product throughout its entire lifecycle. This approach follows the rules recognized by international standards, such as ISO 14040. The LCA is conducted across all input streams to the overall system and at each individual system component. The LCA approach using the **E**co-**I**ndicator **99** (**EI-99**) method is detailed in [15].

Typically, the eco-indicator is assessed for various stages, including materials, production, transportation, energy generation, and disposal issues. Higher eco-indicator values correspond to greater environmental impacts. This process involves several stages: resource analysis, fate analysis, exposure and effect analysis, and damage assessment covering resources, the ecosystem, and human health. The final step is normalization, where a single EI score is assigned to represent the overall environmental burden of the task, see Figure (2).

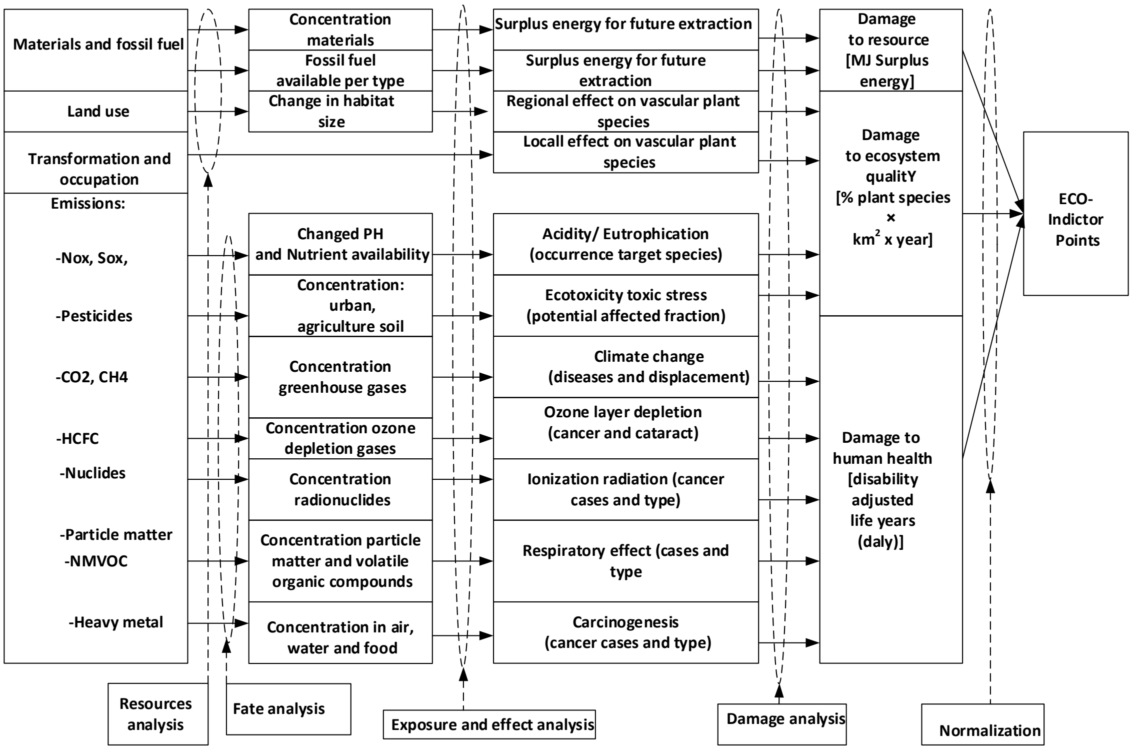


Figure 2: General illustration of approach of the Eco-indicator 99 (EI-99) [15].

Exergoenvironmental Model

The goal of the exergoenvironmental analysis is to evaluate the environmental impact of a system's components. Through this evaluation, the components with the highest environmental impacts can be identified, highlighting key areas for potential improvement. Exergoenvironmental analysis involves three main stages [16]:

1. Exergy analysis is first performed to evaluate the thermodynamic efficiency of the system.
2. Life Cycle Assessment (LCA) is then conducted for the system's components and input streams to assess their overall environmental impact throughout their lifecycle.
3. The environmental impacts identified in the LCA are allocated to the exergy streams within the system. This leads to the calculation of exergoenvironmental variables, enabling a comprehensive exergoenvironmental assessment.

The environmental impact assessment is accomplished via the Eco-indicator 99. The unit of environmental indicator 99 is termed Eco-indicator point (Pt) or milli-point (mPts). The absolute value of the points is not very important as the main task is to compare virtual differences among products or components. The scale is selected in such that the value of 1 Pt represents one-thousandth of the yearly environmental load of one average European citizen [17]. The practice and manual for the designer of eco-indicator 99 are presented in [17] and [15], respectively.

The environmental impact of fuel is a significant factor in exergoenvironmental modeling. The impact of fuel production depends on the production process and the country in which it is produced. For the current analysis, the average environmental impact value of natural gas in Europe was adopted, which is 143.9 mPts/kg [6]. For our natural gas, this was converted to 11,100.3 mPts/MWh. The eco-indicator considers both the production process and the energy consumption involved throughout the component's life cycle. The production process varies by manufacturers, and it is challenging to obtain accurate data, since this information is often kept confidential [10]. The first step of the Life Cycle Assessment (LCA) is to evaluate the Eco-indicator for the extraction of materials used in production processes, measured per kilogram of material, as presented in Table (3) [18].

Table 3: Eco-indicator for materials at simple gas turbine system.

Component	Material	Percent of material	Eco'99 indicator mPts/kg	Points mPts/kg	Total mPts/kg
Air Compressor	Steel	33%	86	28.4	131
	Steel low alloy	45%	110	49.5	
	Cast iron	22%	240	52.8	
Combustion Chamber	Steel	33%	86	28.4	729
	Steel high alloy	77%	910	700.7	
Expander/ Turbine	Steel	25%	86	21.5	202
	Steel high alloy	75%	910	180	

The second step involves evaluating the total **E**co-**I**ndicator (EI) for various components, taking into account their weight, embodied energy of the material, manufacturing process, and disposal, as presented in Table (4) [8]. The EI of each component is then converted into an EI rate by factoring in the projected equipment lifetime, which is estimated at 25 years with 7,500 operating hours per year.

Table 4: Components' environmental impact in life cycle assessment.

	Weight (ton)	Material mPts/kg	Process mPts/kg	Disposal mPts/kg	Total mPts/kg	Total mPts	Total mPts/h
Compressor	170	131	11.7	-70	71.7	12359000	65.91
Combustion chamber	108.2	729	20	-70	585	73468000	391.83
Gas turbine	181.4	202	11.7	-70	645.7	26067000	139.02

Following an analogous approach to the exergoeconomic model, the exergoenvironmental model assigns to each stream an environmental impact rate B_k (measured in milli-points per hour, mPts/h) and an environmental impact per unit of exergy b_k (mPts/MWh). Environmental impact balance equations are then formulated to quantify the environmental burdens associated with the system's processes. The total environmental impact rate B is defined as follows [19]:

$$B = b\dot{\Psi} \quad \left(\frac{pts}{h}\right) \tag{27}$$

where b is the environmental impact per unit of exergy, which is related to the production of the stream in Pts per kWh. The environmental impact balance for each component in the system is given by [14]:

$$\dot{B}_P = \dot{B}_F + \left(\dot{Y} + \dot{B}^{pf}\right) \tag{28}$$

The last equation can be written as:

$$b_P \dot{\Psi}_P = b_F \dot{\Psi}_F + \left(\dot{Y} + \dot{B}^{pf}\right) \tag{29}$$

Here $\dot{B}_P$ and $\dot{B}_F$ are the environmental impact rates related to product and fuel respectively, b_P and b_F are the environmental impacts per unit of exergy for product and fuel respectively. The component-related environmental impact $\dot{Y}$, represents the entire life cycle of the component, contains of the following contributions:

$$\dot{Y} = \dot{Y}^{CO} + \dot{Y}^{OM} + \dot{Y}^{DI} \tag{30}$$

Here $\dot{Y}^{CO}$ is the environmental impact that is linked with construction, counting manufacturing, transport and installation, $\dot{Y}^{OM}$ refers to the environmental impact associated with operation and maintenance, and$\dot{Y}^{DI}$ denotes to the environmental impact associated with disposal and $\dot{B}^{pf}$ refers to the environmental impact rate associated with pollutant formation and given by:

$$\dot{B}^{pf} = b_{pf}(\dot{m}_{out} - \dot{m}_{in}) \tag{31}$$

Pollutant material is discharged to the environment such as: CO_2, CO, N_2O, NO_x. In the present work, only the formation of CO_2 in the combustion chamber is considered. The environmental impact value associated with the emission of CO_2 to the environment is taken as 5.45 mPts/kg [15].

The environmental impact rate linked with the exergy destruction within the component is given by:

$$\dot{B}_D = b_f \dot{\Psi}_D \quad \left(\frac{pts}{s}\right) \tag{32}$$

The total environmental impact associated with a component is then given as $\left(\dot{Y} + \dot{B}_D\right)$.

The exergoenvironmental factor is defined as

$$f_{ev} = \frac{\dot{Y}}{\dot{Y} + \dot{B}_D} = \frac{\dot{Y}}{\dot{Y} + b_f \dot{\Psi}_D} \tag{33}$$

The relative environmental impact factor is given by

$$r_{ev} = \frac{b_P - b_F}{b_F} \tag{34}$$

For the components in Figure (1), the exergoenvironmental equations are given by:

<u>For the air compressor:</u>

$$b_2 \dot{\Psi}_2 = b \dot{\Psi}_1 + b_w \dot{W}_{AC} + \dot{Y}_{AC} \tag{35}$$

$$b_F = b_w \tag{36}$$

$$b_P = \frac{b_2 \dot{\Psi}_2 - b_1 \dot{\Psi}_1}{\dot{\Psi}_2 - \dot{\Psi}_1} \tag{37}$$

<u>For the combustion chamber:</u>

$$b_3 \dot{\Psi}_3 = b_2 \dot{\Psi}_2 + b_{fuel} \dot{\Psi}_{fuel} + \dot{Y}_{CC} \qquad 38)$$

$$b_F = b_{fuel} \tag{39}$$

$$b_P = \frac{b_3 \dot{\Psi}_3 - b_2 \dot{\Psi}_2}{\dot{\Psi}_3 - \dot{\Psi}_2} \tag{40}$$

<u>For the gas turbine:</u>

$$b_4 \dot{\Psi}_4 + b_w \dot{W}_{GT} = b_3 \dot{\Psi}_3 + \dot{Y}_{GT} \tag{41}$$

$$b_F = \frac{b_3 \dot{\Psi}_3 - b_4 \dot{\Psi}_4}{\dot{\Psi}_3 - \dot{\Psi}_4} \tag{42}$$

$b_P = b_W$ (43)

The auxiliary equations are given by:

$b_3 = b_4$ (44)

$b_1 = 0.0$ (45)

RESULTS

The thermodynamic properties and exergy at various states are presented in Table (5).

Table 5: properties and exergy at different states.

State	T (°C)	P (kPa)	$\dot{m}\ (\frac{kg}{s})$	h (kJ/kg)	s (kJ/kg.K)	$\psi\ (\frac{kJ}{kg})$	$\dot{\Psi}\ (MW)$
1	25	101.32	132.05	-0.28	5.26	0.00	0.00
2	342.2387	1013.25	132.05	331.09	5.35	304.60	40.22
3	1151.909	962.59	135.48	209.05	6.67	994.05	134.68
4	715.0785	101.32	135.48	-339.05	6.88	386.12	52.31
5	32.7	1013.25	3.43	-4484.86	9.28	309.07	171.71

The power output of the gas turbine, the power consumed by the air compressor, and the resulting net power were calculated as follows:

$\dot{W}_{GT} = 74.258$ MW

$\dot{W}_{AC} = 43.758$ MW

resulting in a net power output of $\dot{W}_{net} = 30.5$ MW. Using equation (7), the chemical exergy of the natural gas fuel was calculated to be 170.6445 MW.

Figure (3) presents the exergetic efficiencies of the three main components, as well as that of the overall gas turbine power unit. Notably, the combustion chamber exhibits a relatively low exergetic efficiency of **55.01%**, which plays a major role in the low overall exergetic efficiency of the system, measured at just **17.76%**.

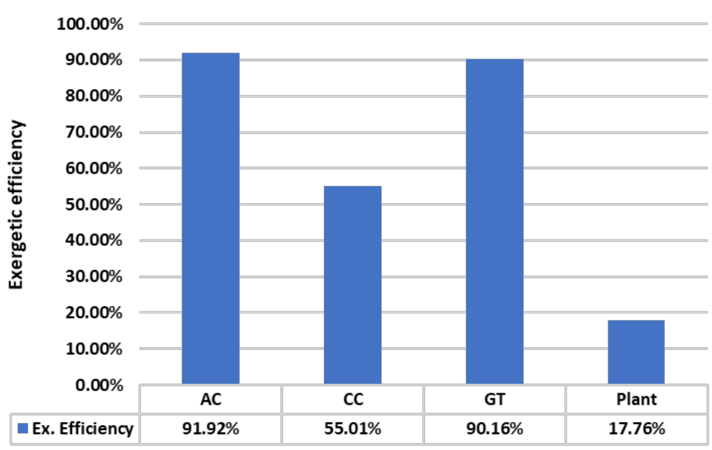


Figure 3: Exergetic efficiency.

Figure (4) illustrates the distribution of the input exergy (fuel exergy), the exergy losses to the environment via the gas turbine exhaust, and the exergy destruction within the three main components. The exergy losses through the exhaust were calculated to be 52.31 MW, while the exergy destruction in the air compressor, combustion chamber, and gas turbine amounted to 3.84 MW**,** 77.25 MW, and 8.11 MW, respectively. This results in a total exergy destruction of 88.89 MW for the entire gas turbine power unit

The input exergy comprises physical exergy (1.06 MW) and chemical exergy (170.65 MW**)**, yielding a total input exergy of 171.71 MW. The difference between the total input exergy and the sum of exergy destruction and exergy loss **(**88.89 MW + 52.31 MW = 141.20 MW**)** corresponds to the net power output, which is 30.51 MW.

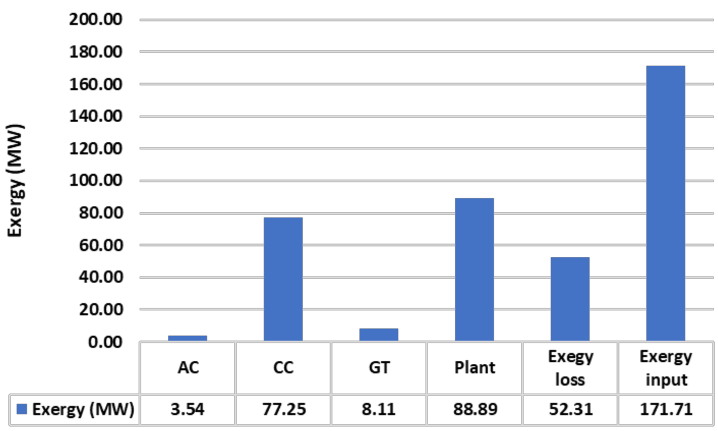
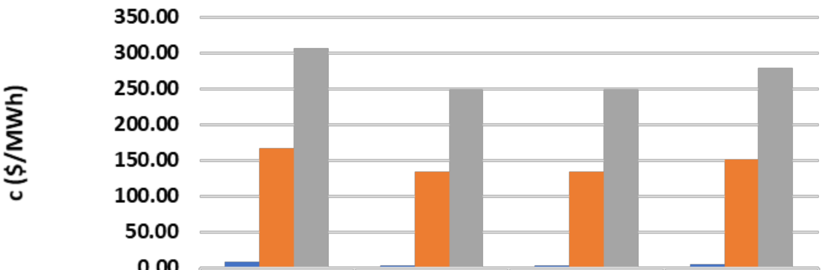


Figure 4: Exergy balance.

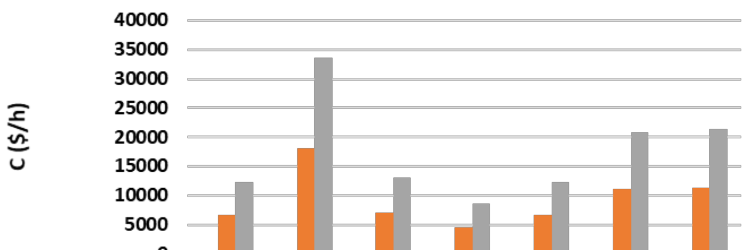
Using equation (9), the hourly operating costs of the three main components were calculated to be \$50.03/h for the compressor, \$30.02/h for the combustion chamber, and \$100.06/h for the gas turbine. Subsequently, by solving equations (15–19), the unit exergy cost of each stream (expressed in \$/MWh) was determined and illustrated in Figure (5). To account for regional variations in fuel pricing, the unit costs were evaluated under three different fuel price scenarios: \$0.00/MWh, \$66.00/MWh, and \$124.194/MWh. The findings clearly indicate that fuel price has a substantial impact on the unit cost of each stream. For example, the cost of the work output exhibits a wide variation, increasing from \$4.91/MWh at zero fuel cost to \$279.49/MWh at the highest fuel price considered.



	c2	c3	c4	cw
zero $/MWh	7.30	2.53	2.53	4.91
66 $/MWh	166.04	134.08	134.08	150.83
124.194 $/MWh	306.01	250.08	250.08	279.49

Figure 5: The unit cost of each stream in $/MWh.

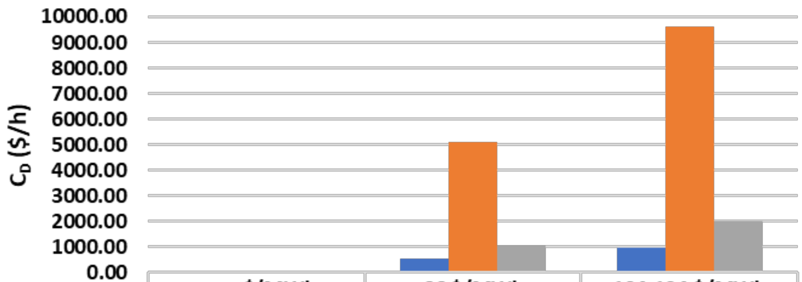
The hourly cost of each stream is obtained by multiplying its unit exergy cost, as shown in Figure (5), by the corresponding exergy flow. The resulting hourly costs are illustrated in Figure (6). The results clearly indicate that fuel cost plays a critical role in shaping the hourly cost distribution across the streams.



	C2	C3	C4	CW-NET	CW-AC	CW-GT	Cfuel
zero $/MWh	293	340	132	150	215	365	0
66 $/MWh	6679	18058	7014	4600	6600	11201	11333
124.194 $/MWh	12309	33680	13082	8525	12230	20755	21325

Figure 6: The hourly cost of each stream in $/h.

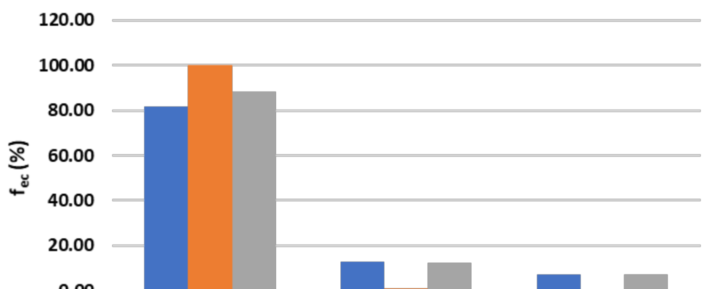
Figure (7) presents the hourly cost of exergy destruction for the three main components, expressed in $/h. This cost is largely influenced by the extent of exergy destruction within each component and the unit cost of the fuel supplying the system (in $/MWh). Among the components, the combustion chamber exhibits a markedly higher exergy destruction cost compared to the gas turbine and compressor. This is primarily attributed to the substantial exergy destruction occurring in the combustion chamber, as previously illustrated in Figure (3).



	zero $/MWh	66 $/MWh	124.194 $/MWh
AC	17.38	533.26	988.12
CC	0.00	5098.53	9594.02
GT	20.50	1087.07	2027.48

Figure 7: The hourly cost of exergy destruction in $/h.

The thermoeconomic factor was calculated under three different fuel cost scenarios and is presented in Figure (8). As illustrated, the thermoeconomic factor for the combustion chamber reaches 100% when the fuel cost is zero, indicating that the capital cost is the sole contributor to the total cost. However, as the fuel price increases to $66/MWh and $124.194/MWh, the cost associated with exergy destruction becomes increasingly significant. This shift results in a notable decrease in the thermoeconomic factor, highlighting the growing dominance of fuel-related operating costs.



	zero $/MWh	66 $/MWh	124.194 $/MWh
AC	81.85	12.81	7.35
CC	100.00	0.91	0.49
GT	88.44	12.60	7.18

Figure 8: The thermoeconomic factor.

The relative exergoeconomic factor is illustrated for the three fuel price scenarios in Figure (9). In the free fuel price scenario, the factor is undefined due to the specific fuel price being zero. For the other two scenarios, the factor is significantly higher for the combustion chamber compared to the other components. This is primarily attributed to the elevated specific product cost of the exhaust gases exiting the combustion chamber, which results from the high fuel price.

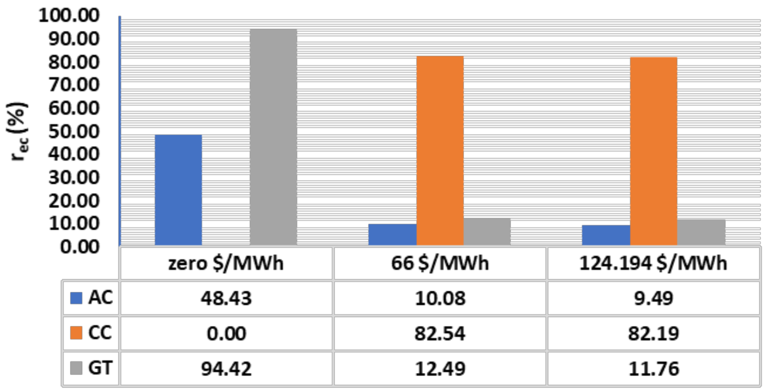


Figure 9: The relative exergoeconomic factor.

By solving equations (35–45), the environmental impact (EI) rate per unit of exergy for the mechanical power (b_W) was determined to be 24,550 mPts/MWh. The environmental impact for each state expressed in both mPts/MWh and mPts/h is presented in Table (6). As shown, the EI at the combustion chamber outlet (State 3) is significantly high, amounting to 2,980,720.282 mPts/h. This value far exceeds the EI at the compressor outlet (State 2) and that of the exhaust gases discharged into the atmosphere (State 4). The total environmental impact for the three streams is 5,212,856.600 mPts/h, with Stream 3 accounting for the largest portion, representing 57.18% of the total EI.

Table 6: Environmental Impact (EI) for cycle's various streams.

State	$\dot{\Psi}$ (MW)	b (mPts/MWh)	B (mPts/h)	Percentage
2	40.22	26709.96203	1074344.865	20.61
3	134.68	22132.23507	2980720.282	57.18
4	52.31	22132.23507	1157791.453	22.21
Total			**5,212,856.600**	

The environmental impact (EI) value for mechanical work is calculated to be 24,550 mPts/MWh. Based on this, the EI associated with the turbine's gross power output (74.26 MW) amounts to 1,823,067.853 mPts/h. This total is distributed between the compressor power consumption (43.76 MW), which accounts for 1,074,278.95 mPts/h, and the net power output (30.5 MW), contributing 748,788.9029 mPts/h. Table (7) presents the environmental impacts of fuels, products, exergy destruction, the three main components, and their respective environmental impact coefficients. As illustrated, the combustion chamber exhibits the highest environmental impact rate across the system's life cycle, at 392 mPts/h, followed by the gas turbine at 139 mPts/h. This is primarily attributed to their material composition: 77% and 75% of high steel alloy, respectively, which carries a significant environmental impact rate of 910 mPts/kg over its life cycle.

Table 7: Exergoenvironmental analysis findings of system components.

	$\dot{\Psi}_D$ (MW)	b_F mPts/MWh	b_P mPts/MWh	$\dot{B}_D$ mPts/h	$\dot{Y}$ mPts/h	$\dot{B}_D + \dot{Y}$ mPts/h	f_{ev} %	r_{ev} %
AC	3.54	24550	26710	86795	66	86861	0.076	8.80
CC	77.25	11100	20183	857503	392	857895	0.046	81.82
GT	8.11	22132	24550	179433	139	179572	0.077	10.93
Total	**88.89**			**1123731**	**597**	**1124328**		

The exergy destruction of the combustion chamber, gas turbine, and air compressor accounts for 44.99%, 4.72%, and 2.06%, respectively, of the total fuel input exergy (171.71 MW). Consequently, the environmental impact rate of the combustion chamber is notably high, reaching 857,503 mPts/h.

The relative environmental impact factor (r_{ev}) of the combustion chamber is the highest among the components, at 81.82%. This is primarily due to the substantial difference in environmental impact (EI) between states 3 and 2, which reflects the influence of the fuel introduced into the combustion chamber. The exergoenvironmental factor (f_{ev}) is comparatively low, as the component-related environmental impact rate ($\dot{Y}^{\cdot}$) is minimal in relation to the environmental impact rate due to exergy destruction ($\dot{B}_D$) for all three components.

The total environmental impact of the three main components of the gas turbine power plant is estimated at 1,124,328 mPts/h. The individual contributions are 7.73% for the compressor, 76.30% for the combustion chamber, and 15.97% for the gas turbine. The dominant contribution from the combustion chamber is attributed to the high irreversibility of the combustion process, whereas both the gas turbine and air compressor exhibit relatively high exergetic efficiencies, as shown in Figure (2).

CONCLUSIONS

In this study, exergy, exergoeconomic, and exergoenvironmental analyses were conducted for a 47 MW nominal capacity gas turbine operating power unit. The exergy analysis indicated that the overall exergetic efficiency of the unit was quite low, mainly due to the poor performance of the combustion chamber. Due to the unavailability of actual cost data for the main components, a widely accepted specific cost of $550,000/MW was used. The total cost was distributed as follows: 50% for the gas turbine, 25% for the air compressor, 15% for the combustion chamber, and the remaining 10% for auxiliary components. The thermoeconomic analysis employed the Specific Exergy Costing (SPECO) method to determine the specific exergy cost of each stream. Since fuel prices differ by region, the analysis was performed under three different fuel price scenarios. Results showed that the specific fuel cost ($/MWh) significantly impacts the specific exergy cost of the streams, the thermoeconomic factor, and ultimately the unit cost rate of the mechanical power generated. The Life Cycle Assessment (LCA) was conducted using the Eco-Indicator 99 (EI-99) method. This approach evaluates environmental impacts across all life cycle stages, including materials, production, transportation, energy generation, and disposal. In this method, higher eco-indicator (EI) values correspond to greater environmental impact. Given that exergy destruction in the combustion chamber was the highest among all components, its associated environmental impact was also significantly greater compared to the air compressor and gas turbine. Additionally, the EI associated with material inputs $\dot{Y}$ was found to be negligible when compared to the EI of exergy destruction for all three components. As a result, the exergoenvironmental factor was considerably low.

NOMENCLATURE

Symbols		AC	air compressor	ev	environmental
T (K)	temperature	CC	combustion chamber	AC	air compressor
P (kPa)	pressure	GT	gas turbine	CC	combustion chamber
LHV	lower heating value	b (mpts/MWh)	Specific stream environmental impact	GT	gas turbine
$\dot{m}\ (\frac{kg}{s})$	mass flow rate	$\dot{B}\ (\frac{mpts}{h})$	stream environmental impact rate	**Superscript**	
$\dot{Q}\ (W)$	heat transfer rate	$\dot{Y}\ (\frac{mpts}{h})$	component environmental impact rate	pf	pollutant formation
$\dot{W}\ (W)$	mechanical power	**Subscripts**		CO	construction
$\dot{Z}\ (\frac{\$}{h})$	capital cost rate	0	reference state	OM	operating and maintenance
$\dot{C}\ (\frac{\$}{h})$	stream cost rate	a	air	DI	disposal
h (kJ/kg)	enthalpy	i	inlet	**Greek**	
s (kJ/kg.K)	entropy	e	exit	$\psi\ (\frac{kJ}{kg})$	exergy
c ($/MWh)	specific cost	q	heat	$\dot{\Psi}\ (W)$	exergy rate
n (years)	time period	k	component	ε	exergetic efficiency
N (hours)	operating hours	D	destruction	φ	maintenance factor
i (%)	interest rate	F	fuel		
Z ($)	capital cost	P	product		
CRF	Capital recovery factor	ec	economic		

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