Exergoeconomic Analysis for a Two-Shaft Industrial Gas Turbine Engine

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In this work, the performance of a two-shaft industrial gas turbine engine inspired by SGT-750 , one of best technology at Siemens, is analyzed thermodynamically and economically. The modelling and analyzing process for the proposed system was executed through a software package called IPSEpro and validated with manufacturers' published data. Exergy analysis, based thermodynamics laws with mass conservation, provides valuable information about locations, magnitudes and types of wastes energy in the thermal systems. Exergoeconomic analysis, the amalgamation of exergy with economics, is useful tool to appraise the gas turbine engine cost-effectiveness. The Specific Exergy Costing method is selected in exergoeconomic evaluation because it is the most widely used reported in the literature and provides reliable results. The performance of a gas turbine engine was investigated for different load variation and climatic conditions. The result shows that the main source of irreversibilities take place in the combustion chamber, compressor and high-pressure turbine, respectively, which constitute to about 96 % of total exergy destruction. The exergetic efficiency and exergy loss rate of the proposed system are about 38.4% and 11.8% respectively. The combustion chamber has the highest value of cost (1312.9 $/h) among other components and the source losses may attribute to the component performance. The production cost of the gas turbine engine based on exergoeconomic evaluation is 12.1 US$/GJ.

Keywords: exergy, exergoeconomic, industrial, gas turbine, irreversibilities.

1. Introduction

Electrical power needs have of late increased due to increased population growth and modernization leading to heightened fossil fuel consumption and higher pollution and greenhouse gases release. Low supply and high demand for the scarce non-renewable energy resources has led to rise in their prices. This has encouraged research to aim and concentrate on renewable energy resources or improving the efficiency of energy-conversion processes for non-renewable resources. Large amounts of natural and economic resources are used up by thermal energy systems contributing to significant unwanted climate changes. Systems must therefore be designed and operated in an effective manner with the aim of making them eco-friendly. Primarily, an appropriate assessment is done using thermal examination tools to find the areas, extents and categories of wastes and losses in the systems. This evaluation process is important as it assists in system modification and improvements. Energy and exergy analysis are the prime evaluation tools employed for thermal energy systems optimization [1], [2].

Owing to the diverse energy resources, exergy performs a great role in sustainable development and the concerns about the quality and quantity of energy. In sustainability, exergetic efficiency is deemed a key element and it is inversely proportional to resource depletion i.e. increases with a decrease in resource depletion and vice versa. This exergy principle has a noteworthy influence on energy, the environment and sustainable development and the utmost impact on the latter is the energy conversion efficiency. Increasing the efficiency of upcoming thermal power plants is aimed at decreasing the rate of fuel consumption, pollution and production costs. By sustainable development, we are simply delaying the exhaustion of non-renewable resources by lowering the usage of fossil fuels. Natural gas, though a fossil fuel, is deemed sustainable energy as it poses minimal environmental hazards.

Industrial and aero-derivative gas turbines are preferable for power generation globally attributable to low costs of installation, faster installation, flexibility in their operation and can easily be incorporated with thermal energy systems. Advancements in gas turbine technologies are weighty challenges experience by researchers and manufacturers. Methods to advance the technology is by improving the gas turbine or by thermal integrated systems e.g. steam turbines, desalination, cooling and heating systems.

GT engines have been investigated using the exergy analysis technique. Evaluation of various factors such as pressure ratio, inlet air temperatures and turbine inlet conditions on the working of GT engines has been carried out by Chad Et al [3]. The parameters were observed to have noteworthy effects on the performance of the engines and hence need optimization so as to attain optimal performance.

Al-Doori did an exergetic analysis on an existing gas power plant with 159MW capacity taking into account variations in ambient temperature [4]. The assessment aimed at exergy obliteration and exergetic efficiency parameters. The results that were found can simply be recapped as follows: first, combustor and turbine irreversibilities are high, second exergy destruction and exergetic efficiency are significantly affected by ambient temperatures. This was later verified by Ebadi and Gorji-Bandpy [5].

Egware and Obanor [6] analyzed GT power plants for numerous loads and turbine inlet temperatures establishing the inverse proportionality of load and turbine inlet temperature; these outcomes are in consonance with previous studies [7], [8]. Abam, et al., analyzed the effects of component efficiency, ambient temperature and pressure ratio on exergetic efficiency and establishing an inversely proportional relationship between temperature and exergetic efficiency [9]. Exergetic efficiency increased as the pressure ratio rose until the exergetic efficiency reached maxima before starting to decrease. Component efficiencies were observed to vary directly with exergetic efficiency. In a broad parametric study (thermodynamic modelling) done by Ameri and Enadi on GT units in an Iranian power plant proves that maximum exergy obliteration occurs in the ignition chamber because of the temperature difference between working fluid and burner, and the turbine inlet temperature has a substantial, and inversely proportional, effect on exergy destruction [10]. Mehta also performed a research to explore regenerative gas-turbine engines at different parameters, where frictional losses were quantified via isentropic efficiency. Portions of energy losses were recovered through exhaust gases by this regenerative modification thus raising engine performance [11].

Exergoeconomic methodology, a term first proposed by Tsatsaronis, is an effective tool that pools the concepts of exergy and economics to evaluate the cost-effectiveness of a thermal system. The methodology is today widely used by researchers in their study of various thermal uses [12]. Moustafarash and Ameri recently carried out an exergoeconomic examination of an unsophisticated cycle gas turbine in the Montazer Ghaem power plant situated in Iran [13]. Another analysis was carried out by Turan and Aydin on LM6000 aero-derivative GT engine [14].

Almutairi et al. submitted two exergoeconomic analysis of a GT engine using modified reheat and intercooling systems [15], [16]. Three mutual observations can be deduced from those studies: To start with, the combustion chamber is considered to be the central component from an exergoeconomic point of view, then the hot section components and lastly the cold section. Secondly, the configuration of the gas turbine had a significant effect on costs of product and components. The third observation was that the type of gas turbine determines the technical options to improve cost-effectiveness.

However, with the advantageous gas turbine for power production, there is still no studies utilizing exergetic analysis were identified that evaluated an advanced two-shaft industrial gas turbine engine. It is therefore worthy researching in this area to improve evaluation of both existing and future projects.

This study is aimed at contributing to the following work as follows:

1. Developing a thorough and broad prototype for a two-shaft industrial GT's centered on exergy study using real data.

2. Simulating gas turbine engine performance using the IPSEpro software in order to determine the design point (DP) and an off-design point (ODP) of different climatic conditions.

3. Examining effects of load vibration on exergy destruction across all components.

4. Applying exergoeconomic analysis to an advanced two-shaft industrial gas turbine engine.

2. Case study

The proposed gas turbine engine in the present work inspired by SGT-750, one of best technology at Siemens. In November 2010, Siemens introduced the STG-750 industrial gas turbine (shown in Figure 1) with a low capacity for power output, with the aim of increasing the selection range for end users around the world. The STG-750 is considered a reliable engine distinguished by high efficiency and low emission levels across a wide range of loads, with the potential for dual function due to its twin shaft; this was not possible in the previous single-shaft engines, which were limited to power generation only. The DLE combustor was used to attain high stability combustion to avoid the increase in nitrogen content caused by rapid changes in fuel composition. The exhaust flow temperature is relatively high, which is useful for combined cycle and multi-generation applications [17].
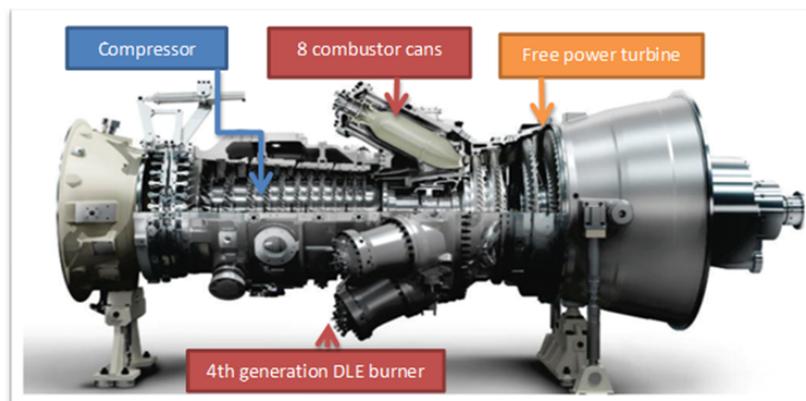
Figure 1 Siemen's STG-750 industrial gas turbine [17]

The STG-750 engine consists of an axial compressor, combustor, compressor turbine, power turbine and generator. The Schematic diagram of a two-shaft industrial gas turbine engine is illustrated in Figure 2. The compressor has 13 stages with a pressure ratio of 23.8 and is directly connected to the compressor turbine via the first shaft, whereas the power turbine is connected to the generator via the second shaft. Both the compressor turbine and power turbine have two stages, and the former is air cooled while the latter is not. The compressor has a special arrangement in rows with bleeding locations to raise performance during part loading and start up.

In general, the STG-750 engine has low life cost with high applicability in a wide range of applications. The performance data in Table 1 are for natural gas fuel under ISO conditions.

Table 1 Siemen's STG-750 gas turbine performance data[18]

GT model	STG-750
Power output (MPa)	37.03
Thermal efficiency (%)	39.5
Heat rate (KJ/KWh)	9,120
Pressure ratio	23.8
Exhaust mass flow (kg/s)	114.2
Exhaust temperature flow (°C)	459
Frequency (Hz)	50/60

Two-shaft industrial gas turbines have the advantage of low starting power with low-quality exhaust compared to the single–shaft engines. Furthermore, two-shaft engines are designed with a fixed speed generator, which is required for highly efficient operators in order to avoid over-speeding risk on load rejection in the electrical grid.

The ramp rate of the STG-750 is 3.75 MW/min (i.e., it can recover the full load within 10 min), which represents 10% of full load and is considered highly reasonable.
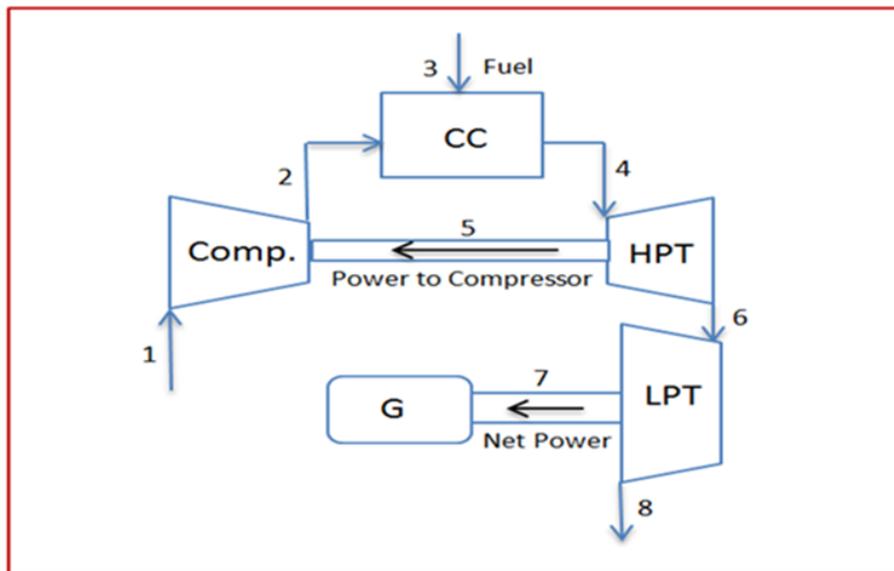
Figure 2 Schematic illustration of the proposed gas turbine engine

3.   Methodology

In this study, exergy and exergoeconomics were studied at three kinds different loads: 50%, 75% and 100%. The ambient temperature at each load was studied for 288 K, 298, 308 K and 323 K. The reference temperature was taken to be 288 K and ambient pressure 1.01 bar.

The following assumptions about a gas turbine model were made:

- Operation of the gas turbine was done at steady state.

- The concept of the ideal gas mixture was applied in air and combustion products.

- Negligible kinetic and potential exergies.

- There was complete combustion and Nitrogen gas (N2) was considered inert.

- Heat transferred from the combustor was 2% that of natural gas lower heating calorific value (LHV).

- The supplied natural gas was used as fuel (see Table 2 for composition).

Table 2 Molar fraction of the natural gas components

Component	Molar fraction (%)
Methane (CH_4)	93.34
Ethane (C_2H_6)	0.211
Propane (C_3H_8)	0.029
Nitrogen (N_2)	6.42

The fuel was supplied to the combustor at high pressure with different values of mass flow rate, depending on load and inlet temperature to the combustion combustor. The mass flow rate of the air stream also varied in the cold section.

Table 3 Design parameters of the radial-axial turbine operating on silica oil MM

Component	Molar fraction (%)
Nitrogen (N_2)	77.48
Oxygen (O_2)	20.59
Water (H_2O)	1.9
Carbon dioxide (CO_2)	0.03

3.1.   *Exergy analysis methodology*

Exergy can also be referred to as available energy. It is the full amount of useful work that can be got from a system at reversible operation (an activity that brings the system in equilibrium with the surrounding) and can be articulated as:

$$\dot{E}_x = \dot{E}_{ph} + \dot{E}_{ke} + \dot{E}_{pe} + \dot{E}_{ch} \tag{1}$$

It is worth noting that exergy of a system in equilibrium with the surrounding/environment is zero. Where $\dot{E}_{ph}$, $\dot{E}_{ke}$, $\dot{E}_{pe}$ and $\dot{E}_{ch}$ are physical exergy, kinetic exergy, potential exergy and chemical exergy respectively. Specific exergy of a stream is the ratio of total exergy to the mass flow rate:

$$e_x = \frac{\dot{E}_x}{\dot{m}} \tag{2}$$

Consequently, precise exergy of a definite stream equals the sum of specific exergies expressed as:

$$e_x = e_{ph} + e_{ke} + e_{pe} + e_{ch} \tag{3}$$

In the present study, specific kinetic exergy e_{ke} and specific potential exergy e_{pe} are negligible. Physical exergy is defined as total useful work that can be obtained from a unit mass of material moving from a specified state (T_s, P_s) to the reference state (T_o, P_o) in purely physical processes [19]. Physical exergy concept can be broken down into mechanical and thermal exergies expressed as follows:

$$\dot{E}_{ph} = \dot{m}[(h_s - h_o) - T_o(s_s - s_o)] \tag{4}$$

when T_s is equal to T_o with the ideal gas relation, the above equation (4) becomes:

$$\dot{E}_{ph} = \dot{m}_e R T_o ln \frac{P_e}{P_o} \tag{5}$$

Chemical exergy is the total valuable energy that is obtainable in a process where a particular system is made to react with substances in the surroundings:

$$\dot{E}_{ch} = \dot{n}[\int y_k \overline{e}_k^{ch} + \overline{R} T_o \int y_k \mathrm{ln} y_k] \tag{6}$$

$\dot{n}$ is number of moles $\overline{e}_k^{ch}$ is molar chemical exergy for constituent k in a mixture, (Can be read from standard chemical exergies tables) [20]. Chemical exergy of a fuel can be expressed as:

$$\dot{E}_{ch} = \dot{n_f} \overline{LHV} \tag{7}$$

As a result of exergy depletion and exergy losses, the amount of exergy exit is always less than inlet for all system components:

$$\dot{E}_i = \dot{E}_e + \dot{E}_d + \dot{E}_L \tag{8}$$

$\dot{E}_d$ and $\dot{E}_L$ represents exergy destruction and loss rates respectively. Owing to irreversibilities within components in a process, $\dot{E}_d$ is proportionate to entropy generation. It can be obtained from the difference in exergy value across the components:

$$\dot{E}_d = \dot{E}_i - \dot{E}_e - \dot{E}_L \tag{9}$$

Exergy losses is interlinked with energy dissipation to the surroundings at the end of a process (e.g. exhaust gases and water). The rate and amounts of energy

conversion is indicated by thermal system efficiency. Thermal efficiency relates input energy (fuel) and work output while on the other hand, exergetic efficiency indicates the amount of work output obtainable from maximum available work.

Exergetic efficiency is the proportion of output exergy to exergy input i.e. ratio of exergy given out to fuel exergy supplied:

$$\eta_{\text{ex}} = \frac{\dot{E}_e}{\dot{E}_i} = \frac{\dot{E}_p}{\dot{E}_f} = 1 - \frac{\dot{E}_d + \dot{E}_l}{\dot{E}_f} \tag{10}$$

Definition of exergetic efficiencies for various components in gas turbines at steady state:

$$\text{Compressor}: \quad \eta_{ex} = \frac{\dot{E}_e - \dot{E}_i}{\dot{W}_c} \tag{11}$$

$$\text{Combustor}: \quad \eta_{ex} = \frac{\dot{E}_e}{\dot{E}_{i1} + \dot{E}_{i2}} \tag{12}$$

$$\text{Turbine}: \quad \eta_{ex} = \frac{\dot{W}_t}{\dot{E}_i - \dot{E}_e} \tag{13}$$

3.2. *Exergoeconomic analysis*

Exergoeconomic analysis focuses on minimizing costs of production and those of inefficiencies. It is a useful tool that helps to decide whether the designed system is viable or not. The SPECO technique is used to assess the costs of streams and exergoeconomic factors, and determining potential improvements to ensure cost efficiency [1], [12].

3.3. *Economic analysis*

The prime outcomes of economic examination are the fuel costs, average equipment purchase cost (EPC) and Operation and maintenance (O&M) costs. Table 4 illustrates some economic input data which used in the proposed economic model. The overall cost balance formula for each component can be expressed by:

$$\dot{C}_{q,k} + \int_i \dot{C}_{i,k} + \dot{Z}_k = \int_e \dot{C}_{e,k} + \dot{C}_{w,k} \tag{14}$$

$\dot{C}$ is flow cost rate in \$/hr (q,w,i,e referred to heat transfer, work, inlet and exit respectively) and $\dot{Z}_k$ is the summation of capital investment costs (EPC) and O&M costs, expressed as:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{15}$$

Input parameters need to be levelized/averaged before using exergoeconomic analysis.

The concept behind price levelization is to correlate the spending expenses/overheads at the start of the venture with a corresponding income with the aim of avoiding non-uniform cash flow. Present worth (PW) also called Net Present Value (NPV) denotes a corresponding value for prices over a specified period with regard to present values. On the other hand, Salvage value (Sv) is a component of depreciation and denotes the projected worth of an asset at the end of service life [1], [14].

$$PW = CIC - S_v \ .PWF \tag{16}$$

Table 4 Economic input data the proposed economic model

Parameter	Unit	Value
Annual operation hours (τa)	h/year	8,000
Engine life time (n)	year	20
Nominal escalation rate (r_n)	%	5.0
Discount rate (i_{eff})	%	6.0
Salvage rate	%	
Fuel price (FP)	$/GJ	5.0
Lower heating value (LHV)	kJ/kg	46,802

$$S_v = j.CIC \tag{17}$$

where:

CIC – capital investment cost

j – % recovery (salvage) rate

PWF – present worth factor which is calculated from:

$$PWF = \frac{1}{(1 + i_{eff})^n}$$

where i_{eff} is the discount percentage and n the number of years.

Capital recovery factor is another important parameter that converts present worth to a series of equal annual payments for a certain duration of time, at a stated discount rate aimed at recovering the initial investment.

$$CRF = \frac{i_{eff}(1 + i_{eff}{}^n)}{(1 + i_{eff})^n + 1} \tag{18}$$

The annual capital cost (ACIC) is given by:

$$ACIC = CRF.PWF(i,n) \tag{19}$$

The hourly Levelized cost of gas turbine engine and its kth component are given by:

$$\dot{Z}^T = \frac{ACIC}{\tau} \tag{20}$$

$$\dot{Z}_k = \dot{Z}^T \frac{EPC_k}{\int EPC_k} \tag{21}$$

where τ represents plant operational hours/year

In energy costing, all streams have costs associated with energy values thus one should consider the total inlet and exit flows/streams for every constituent, work done and heat generation, and how these two interrelate with the surrounding at steady-state operation.

$$\dot{C}_j = c\dot{E}_{x,j} \tag{22}$$

where j can represent an inlet or exit stream, heat transfer and work done, C_j denotes the levelized cost per unit exergy for the jth stream. When the cost rate equation and overall cost expression are combined, the following expression is born:

$$c_{q,k}\dot{E}_{q,k}+ \int_i (c_i\dot{E}_i)_k+\dot{Z}_k= \int_e (c_e\dot{E}_e)_k+c_{w,k}\dot{W}_k \tag{23}$$

An assumption that entering streams are known for all components must be made for one to analyze exit streams using exergoeconomic analysis. EPC and O&M are obtained from economic analyses. A situation may arise where the number of unknowns are more than that of cost balance equivalences. This mostly occurs where there is the amount of entering and exit streams for constituents.. When such circumstances occur, fuel and product rules are used to develop auxiliary equations [1], [21], [22].

3.4.   *Exergoeconomic balance equations*

In determining exergy obliteration and stream price, a linear system of equations is generated when solving the cost balance equations with auxiliaries.

$$\left[\dot{E}_k\right] X [c_k] = \left[\dot{Z}_k\right] \tag{24}$$

where: $\left[\dot{E}_k\right]$ is an exergy rate matrix found from exergy analyses, $\left[\dot{Z}_k\right]$ is the vector of total price achieved from economic analyses and $[c_k]$ is exergetic cost vector.

Below are necessary price balance and auxiliary expressions for all constituents in the recommended system.

Axial Compressors [AC]:

$$\dot{C}_1+ \dot{C}_5 +\dot{Z}_C=\dot{C}_2 \tag{25}$$

$$\dot{C}_1= 0 \text{ [Assumption at reference state]} \tag{26}$$

Combustion Chamber [CC]:

$$\dot{C}_2+ \dot{C}_3+\dot{Z}_{CC}=\dot{C}_4 \tag{27}$$

$$\dot{C}_3=Fuel\ price=Constant \tag{28}$$

High-Pressure Turbine [HPT]:

$$\dot{C}_4+ \dot{Z}_{HPT}=\dot{C}_5+\dot{C}_6 \tag{29}$$

$$\frac{\dot{C}_4}{\dot{E}_4}=\frac{\dot{C}_6}{\dot{E}_6} \text{ [F rule]} \tag{30}$$

Low-Pressure Turbine [LPT]:

$$\dot{C}_6+ \dot{Z}_{LPT}=\dot{C}_7+\dot{C}_8 \tag{31}$$

$$\frac{\dot{C}_6}{\dot{E}_6}=\frac{\dot{C}_8}{\dot{E}_8} \text{ [F rule]} \tag{32}$$

Fuel cost in \$/h can be calculated using the following expression.

$$Fuel\ price = 3600.\tau.FP.LHV.\dot{m}_f \tag{33}$$

The variable of cost per exergy unit $(\dot{C}_1 - \dot{C}_8)$ is solved by using equations (25) to (32).

3.5. *Exergoeconomic factor*

The exergoeconomic factor, f_k, is an important exergoeconomic variable used to assess and enhance thermal systems. The price of the kth constituent can be credited to two sources, the first is connected with exergy related costs such as exergy losses which may be considered as ineffectiveness, and the second connected to non-exergy amounts such as capital outlay and O&M costs. Recognizing the sources of costs is considered useful information that aids to find the relative weight of the two sources which can improve system cost efficacy. The exergoeconomic element f_k can be expressed as:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k} \left[\dot{E}_{d,k} + \ \dot{E}_{L,k} \right]} \tag{34}$$

4.   Result and discussion

In this segment, outcomes of exergy and exergoeconomic analysis are presented for the proposed gas turbine engine. Exergy examination is a useful tool that can assist in determining the locations together with magnitudes of inefficiencies and the types of wastes and losses in an energy system. Improving energy conversion systems is required and represents an essential objective in order to reduce product cost besides environmental impact, and to realize sustainable improvement, particularly when fossil fuels are used.

Table 5 Thermodynamic data for the proposed gas turbine engine at ISO ambient condition

State	Substance	Mass flow [kg/s]	Temp. [K]	Pressure [bar]	Exergy $\dot{E}_{ph}$ [MW]	Exergy $\dot{E}_{ch}$ [MW]	Exergy $\dot{E}_x$ [MW]
1	Air	112.00	288.00	1.01	0.00	1.66	1.66
2	Air	24.11	749.65	24.11	51.41	1.66	53.07
3	Fuel	2.22	288.00	28.13	1.05	103.90	104.95
4	Exhaust gases	114.22	1400.00	21.51	110.49	0.35	110.84
5	Power to compressor				54.54	—-	54.54
6	Exhaust gases	114.22	1023.43	4.50	52.64	0.35	52.99
7	Gross Power				38.77	—-	38.77
8	Exhaust gases	114.22	739.19	1.02	11.74	0.35	12.09
Net Power					37.02	—-	37.02

Table 5 shows exergetic data for the proposed gas turbine engine at ISO condition. Similarly, analyses were conducted at 298K , 308 K and 318 K to show the impact of the climatic condition on the engine performance.
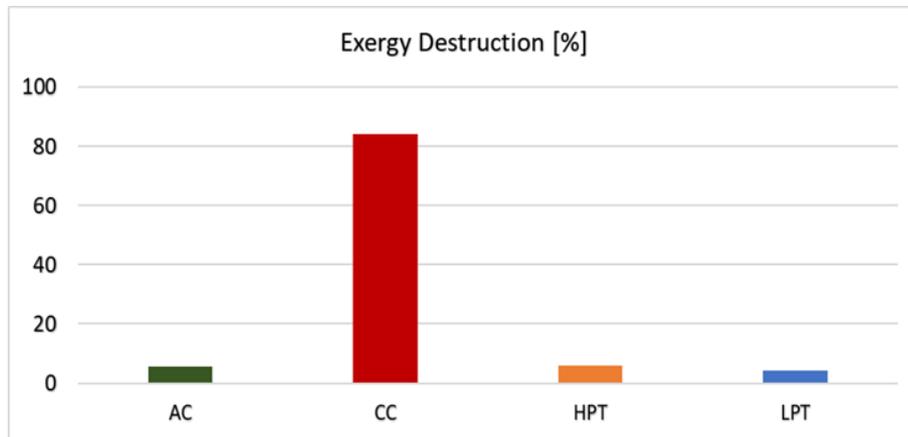
Figure 3 Exergy destruction rate within a component for the proposed gas turbine engine as a percentage of total exergy destruction rate
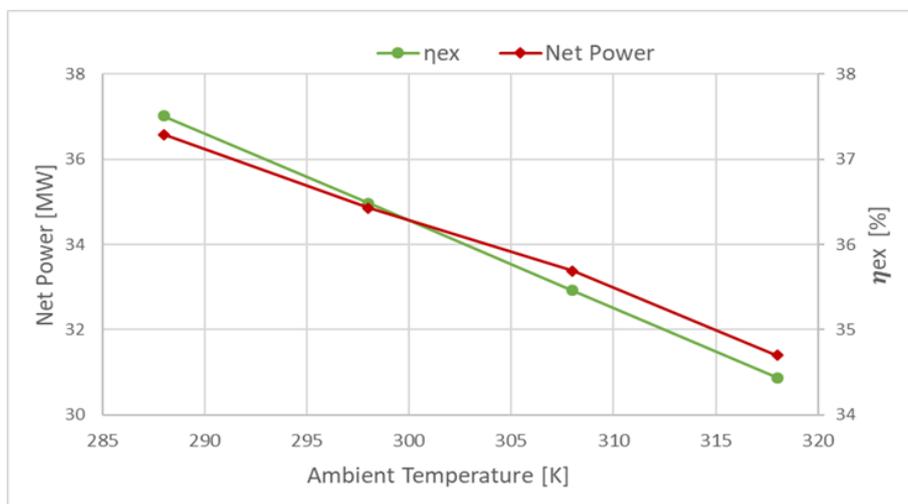
Figure 4 Net power output and exergetic efficiency and versus ambient temperatures

The percentage of exergy destruction rates for all components in a two-shaft industrial gas turbine engine at ISO condition is shown in Figure 2. The highest exergy destruction rate occurs at the combustion chamber due to mixing, large temperature difference, and chemical reaction as confirmed by [3]–[5], [12], [23]. The high-pressure turbine (HPT) embodies the second major source of irreversibility due to friction, high fuel exergy and unrestrained expansion to lower pressure. The exergy destruction level of the axial compressor (AC) has almost the same value due to mechanical coupling effect and high-pressure ratio. The low-pressure turbine (LPT) represent the fourth source of irreversibility due to friction which results from large blade size and a high number of stages.

Figure 4 shows the effect of ambient temperature on the net power output and exergetic efficiency of the GT engine. The ambient temperature variation is govern by the climatic conditions at the GT location. In some places, the ambient temperature variation is limited while in the other sites range variation is wide. Operate the gas turbine engine at low ambient temperatures is always preferable due to low power consumption in the compressor as a result of high air density. High ambient temperatures increase the losses in the compressor despite saving a portion of the fuel in the combustion chamber while the rate of losses is higher. The form of energy also contribute to this degradation in the exergatic efficiency and net power output because the quality of electrical energy is higher than fossil fuel chemical energy, hence the amount of fuel energy saving is lower than energy consumed by the axial compressor. The impact of temperatures variation can be diminished by integrated the gas turbine engine with a low-grade cooling system such as absorption chiller.
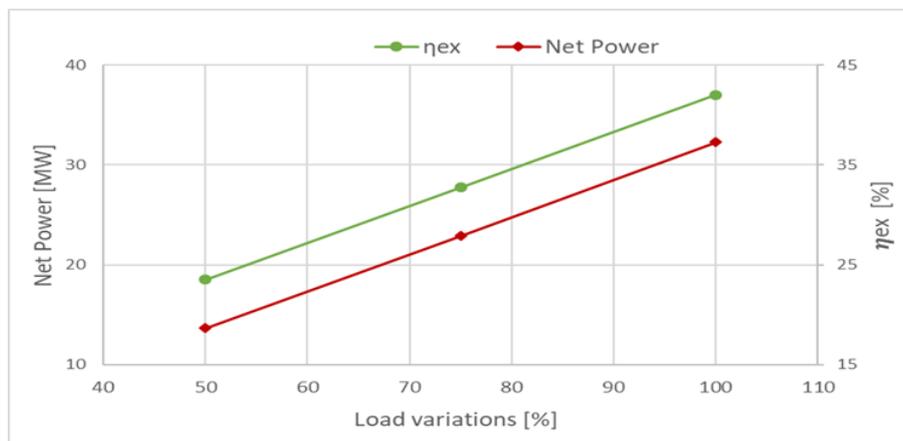

Figure 5 Net power output and exergetic efficiency and versus load variations

Figure 5 illustrates net power output and exergetic efficiency and versus load variations. The electrical demand in the national grid is subject to continuous load variation due to the end-user requirement which is highly affected by climate condition and load daily distribution. Maintain electrical grid stability is important

to confront loads fluctuation. The gas turbine engine is a reliable and attractive choice for electrical power application due to high operational flexibility and quick startup despite that cause thermal stresses and adversely affect the unit lifespan. In stand-alone mode, it's highly recommended to use only for peak loads due to lower efficiency relative to other fossil fuel plants. At part load, the net power output and exergetic efficiency of the proposed gas turbine are decreased and it's highly advisable to operate the engine at full load or minimising the part load duration to guarantee high performance with better energy utilization.
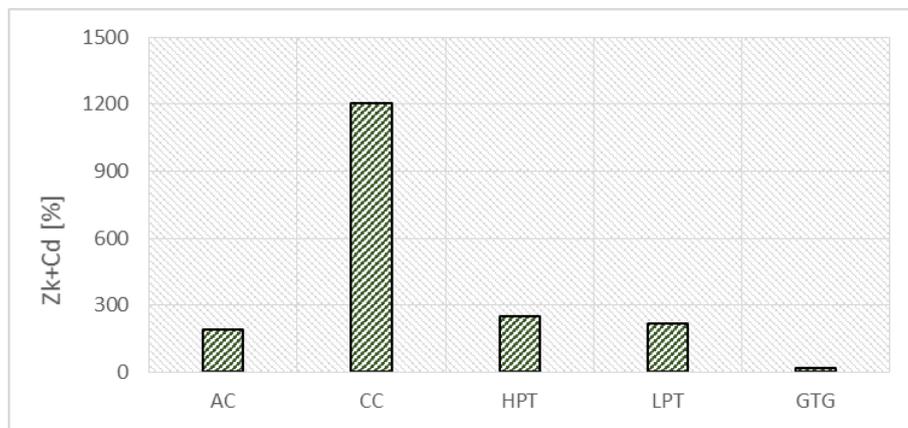
Figure 6 Total cost and exergy destruction costs ($Zk+Cd$) for the two-shaft industrial gas turbine engine
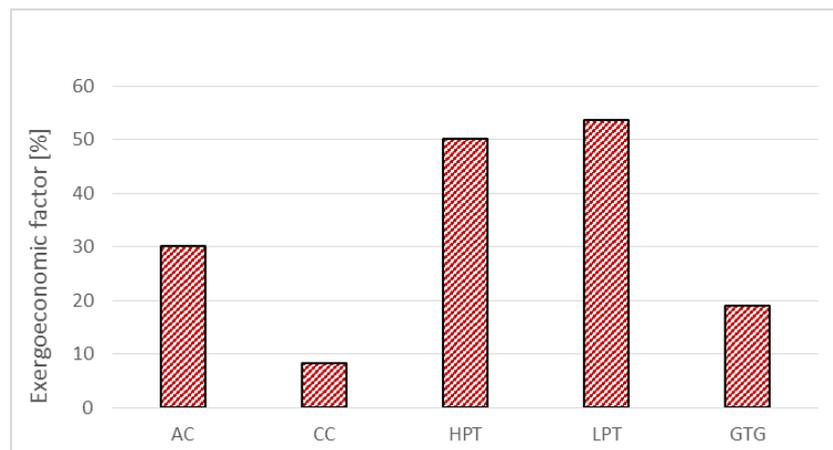
Figure 7 Exergoeconomic factor (f_k) for the two-shaft industrial gas turbine engine

The cost and exergy destruction costs $(Zk + Cd)$ of the two-shaft industrial gas turbine engine components are shown in Figure -6. The combustion chamber is the most important components based on the exergoeconomic criteria, followed by the high-pressure turbine and low-pressure turbine. The proposed gas turbine engine cost-effectiveness can be enhanced according to the status of components on Figure -7. The exergoeconomic factor of the combustion chamber is the lowest, therefore it highly recommends to improve its efficiency at the expense of capital cost to reduce the product cost. For both high-pressure turbine and low-pressure turbine the exergoeconomic factor is about 50 %, so the source of costs are related to exergy destruction and non-exergy as well. Thus, dual action can be taken to improve the entire system economic efficiency through enhance components performance and reduce the capital cost at the same time. For the axial compressor and electrical generator modify the design is required in capital expenses due to low exergoeconomic factor.

5. Conclusions

Exergetic and exergoeconomic analysis for a two-shaft industrial gas turbine engine has been carried out at different working operation conditions. The ambient temperature variation and load fluctuation impact on gas turbine engine performance were investigated. The proposed model has been developed by IPSEpro software and validated with with manufacturer-published data. The results confiemed that the combustion chamber is the main source of irreversibility and the most important component from the exergoeconomic perspective. Enhance the combustion chamber performance can be achieved either by enhancing the mixing or using preheating systems or adjusting the air-fuel ratio. Operate gas turbine engine at full load and low ambient trmperture is preferable due to high net power output and exergetic efficiency. The exergoeconomic evaluation provides useful information about the proposed gas turbine engine through assessing the components individually for the sake of improving the system cost-effectiveness.

6. Acknowledgments

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Nomenclature

$\dot{C}$	Flow cost rate
$\dot{E}$	Exergy rate
$\overline{e}_k^{ch}$	Molar chemical exergy
h	Enthalpy
$\overline{LHV}$	Low heating value in molar basis
$\dot{m}$	Mass flow rate
P	Pressure
R	Gas constant
$\overline{R}$	Universal gas constant
S	Entropy
T	Temperature
V	Velocity
$\overline{R}$	Universal gas constant
S	Entropy
y	Mole fraction

Greek symbols:

η_{ex}	Exergetic efficiency

Subscripts:

ch	Chemical
d	destruction
e	Outlet
i	Inlet
k	Component
ke	Kinetic energy
L	Loss
o	Reference state
ph	Physical
pe	Potentials
S	State
x	Total