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# Advanced exergoeconomic analysis of an electricity-generating facility that operates with natural gas

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ABSTRACT

This paper presents an advanced exergy analysis of an electricity generation facility in the Eskisehir Industry Estate Zone in Turkey. The total electricity generation rate is approximately 55 MW. The exergy efficiency of the system is 0.402 and the total exergy destruction rate of the system is 78.242 MW. The unit exergy cost of electrical power that is generated by the system is 25.660 $/GJ, and the total exergoeconomic factor of the system is 0.247. Advanced exergetic and exergoeconomic analyses were applied to the considered system. The advanced exergoeconomic analysis shows that the combustion chamber, the high-pressure steam turbine and the condenser have great economic improvement potential because of their high exergy destruction cost rates. Similarly, the heat recovery steam generator and the condenser have significant potential because of their investment costs. In addition, suggestions to improve the system economical parameters are provided. Finally, it can be concluded that relations between the components are strong.


## 1. Introduction

Engineering advancement pioneered the development of gas turbines in the early 1900s, and turbines began to be used for stationary electric power generation in the late 1930s. Gas turbines are available in sizes that range from 500 kilowatts (kW) to 250 megawatts (MW). Gas turbines can be used in power-only generation or in combined-heat-and-power (CHP) systems. The most efficient commercial technology for central-station power-only generation is the gas-turbine-steam-turbine combined-cycle plant, whose efficiencies approach 60% of the lower heating value (LHV). Simple-cycle gas turbines for power-only generation are available with efficiencies that approach 40% (LHV). Gas turbines have long been used by utilities for their peaking capacity. However, with changes in the power industry and advancement in technology, gas turbines are now increasingly used for base-load power. Gas turbines produce high-quality exhaust heat that can be used in CHP configurations to reach overall system efficiencies (electricity and useful thermal energy) of 70–80%. By the early 1980s, the efficiency and the reliability of smaller gas turbines (1–40 MW) had sufficiently progressed to be an attractive choice for industrial and large institutional users in CHP applications. The gas turbine is one of the cleanest means to generate electricity; the nitrogen oxide (NOx) emission of some large turbines with catalytic exhaust cleanup or lean pre-mixed combustion is in the single-digit part-per-million (ppm) ranges. Because of their relatively high efficiency and reliance on natural gas as the primary fuel, gas turbines emit substantially less carbon dioxide ($CO_2$) per kilowatt-hour (kW h) generated than any other fossil technology in general commercial use. The oil and gas industry commonly uses gas turbines to drive pumps and compressors. The process industries use them to drive compressors and other large mechanical equipment, and many industrial and institutional facilities use turbines to generate electricity for on-site use. When gas turbines are used to generate power on-site, they are often used in the combined-heat-and-power mode, where the energy in the turbine exhaust provides thermal energy to the facility [1].

Two important problems of the world are environmental pollution and the increasing energy demand. Thus, energy resources must be used more effectively. It is irrefutable that an efficient thermal system produces less green-house gases and uses energy more effectively. Conventional exergy-based analyses can evaluate the effectiveness of an energy conversion system. However, these analyses do not provide enough information about the relations between the components and are inadequate in determining the real improvement potentials. Thus, a thermodynamic analysis method, which is called the advanced exergy analysis, was developed to resolve the deficiencies in the conventional exergy analysis. For example, the exergy destruction, the exergy costs and the investment for any component can be considered to be a result

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**Nomenclature**

| | |
|---|---|
| $\dot{E}$ | exergy rate (kW) |
| $c$ | unit exergy cost ($/GJ) |
| $\dot{C}$ | exergy cost rate ($/h) |
| $f$ | exergoeconomic factor |
| $\dot{m}$ | mass flow rate (kg/s) |
| $P$ | pressure (kPa) |
| $r$ | relative cost difference |
| $T$ | temperature (K) |
| $y$ | exergy destruction ratio |
| $\dot{z}$ | capital investment cost flow rate ($/h) |

*Abbreviations*

| | |
|---|---|
| *AC* | air compressor |
| *CC* | combustion chamber |
| *CHP* | combined heat and power |
| *COND* | condenser |
| *GT* | gas turbine |
| *HPST* | high-pressure steam turbine |
| *HRSG* | heat recovery steam generator |
| *LPST* | low-pressure steam generator |
| *PEC* | purchased equipment cost ($) |

*Subscripts*

| | |
|---|---|
| *D* | destruction |
| *F* | fuel |
| *k* | *k*th component |
| *L* | loss |
| *P* | product |

*Superscripts*

| | |
|---|---|
| *AV* | avoidable |
| *EN* | endogenous |
| *EX* | exogenous |
| *MEX* | mexogenous |
| *UN* | unavoidable |

*Greek letters*

| | |
|---|---|
| $\eta$ | isentropic/energetic efficiency (%) |
| $\phi$ | exergetic efficiency (%) |

of the component itself or other components. The advanced exergy-based analysis simultaneously provides everyone in the formation about the improvement limits of the considered component or the system, which resulted from technical or ecological constraints. This study aimed to evaluate an electricity facility by using the advanced exergoeconomic analyses to determine the correct improvement strategies and the reasons of exergy destructions. In addition, the results were compared with the systems to which the advanced exergoeconomic analysis was applied.

In the literature, there are few papers on advanced exergy- and exergoeconomic-based analyses of power-generating systems [2–13]. In their study, Tsatsaronis and Moung-Ho (2002) were the first to develop the concepts of avoidable and unavoidable exergy destructions, which are used to determine the potential of improving the thermodynamic performance and the cost effectiveness of a system [2]. Cziesla et al. (2006) investigated all components of an externally fired combined power plant according to both avoidable and unavoidable exergy destructions; the associated costs were defined, and the results of their study were discussed [3]. Tsatsaronis (2008) discussed the weaknesses of the conventional exergy-based analyses in developing improvement strategies and presented advanced exergy, advanced exergoeconomic and exergoenvironmental analyses as the solutions to these weaknesses [4]. Kelly et al. (2009) defined the exogenous and endogenous exergy destructions that determine the interactions among components and were the first to present a calculation method. The calculations were expressed using a simple refrigeration cycle and a simple gas turbine cycle [5]. Razmara and Khoshbakhti Saray (2009) investigated the exogenous and endogenous exergy destructions using the engineering method for a simple gas turbine cycle that operated with different fuels. The observed irreversibilities in the components were described and compared for these fuels [6]. Morosuk and Tsatsaronis (2009) used the advanced exergy analysis to evaluate a simple gas turbine cycle and discussed their calculation methods in details [7]. Tsatsaronis and Morosuk (2010) used the advanced exergy analysis to study a natural gas liquefaction plant that used a three-stage refrigeration cycle. They defined the improvement potentials and the interactions among the components [8]. Morosuk et al. (2012) analyzed a natural-gas degasification plant, which produced electricity, using advanced exergy and advanced exergoenvironmental methods. They concluded that the expander II, the heat exchanger II and the pump deserved the most attention in improving their thermodynamic efficiency and reducing their environmental impact [9]. Wang et al. (2012) analyzed a power plant that operated under supercritical conditions using the advanced exergy analysis and proposed suitable optimization strategies. The authors recommended that the generator were improved first, followed by the turbines [10]. Petrakopoulou et al. (2012) studied a combined power plant using both advanced exergy analysis and conventional analysis and demonstrated the superiority of the former. The authors showed that the advanced exergy analysis provides a wide range of optimization strategies and improvement potentials [11]. Petrakopoulou et al. (2012) used the advanced exergy and advanced exergoenvironmental analyses to study a combined power plant. The authors discovered that 68% of the environmental impact of the system was unavoidable [12]. In Refs. [13,14], the advanced exergoeconomic analysis was applied in a combined (CHP) system and an oxy-fuel power plant with $CO_2$ capture, and the methodology that was used to perform the advanced exergoeconomic analysis was explained in a detail.

In this paper, the electricity-generating facility that operates with natural gas was described in the second section. The application of the advanced exergoeconomic methods was defined in detail in the third section. Then, in the fourth section, the obtained results were discussed and compared with some systems in the literature. Finally, the required recommendations and the interpretations that address the considered system were provided.

## 2. System description

An electricity-generating facility that operates with natural gas is shown in Fig. 1. This system is located in the Eskişehir Industry Estate Zone, Turkey. It consists of a compressor (AC), a combustion chamber (CC), a gas turbine (GT), a heat recovery steam generator (HRSG), a high-pressure steam turbine (HPST), a low-pressure steam turbine (LPST) and a condenser (COND). Approximately 55 MW of electric power is generated by the system, but the process steam cannot be used because of the chemicals in the steam. For a 45.07 air/fuel ratio, the combustion equation of natural gas is as follows [15–18]: