Exergoeconoenvironmental analysis as a new concept for developing thermodynamically, economically, and environmentally sound energy conversion systems

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1. Introduction

In recent years, intensive efforts have been put forth worldwide to improve the design and operation of energy conversion systems in response to both energy and environmental concerns (Esen et al., 2006). Various approaches, based on concepts like emergy, life cycle assessment (LCA), energy, and exergy, have been developed in order to make decisions on the productivity and sustainability of energy conversion processes (Dadak et al., 2016). Among the techniques developed to date, exergy-based methods have great potential for addressing these issues (Mojarab Soufiyan et al., 2016). In simple terms, exergy is the maximum capacity of a given kind of energy or material to generate useful work when it comes to a complete equilibrium with a reference environment, often take to be its surroundings (Esen, 2008; Genc et al., 2017; Mandegari et al., 2015). The maximum in this statement implies reversible processes are used.

The exergy concept has proven to be a more powerful tool than the traditional energy analysis because of its capability for revealing the irreversibility aspects of energy conversion processes...
Exergy analysis has become increasingly popular in the last two decades for scrutinizing energy systems from sustainability,  
ecological and productivity viewpoints (Pelvan and Özilgen, 2010). The thermodynamic inefficiencies of energy systems can be  
reliably located and quantified using the exergy concept (Fadare et al., 2010; Ohijeagbon et al., 2013; Ozilgen and Sorgüven, 2011).  
Exergy analysis has become increasingly popular in the last two decades for scrutinizing energy systems from sustainability, efficiency,  
and productivity viewpoints (Pelvan and Özilgen, 2017; Zisopoulos et al., 2015). This could be ascribed to the fact that there is a direct  
association between sustainability and environmental/ecological facets (Dincer and Rosen, 2005). To address this issue, various approaches  
have been proposed and applied in the past that combine exergy concepts with economic and environmental constraints. Exergy-based methods have  
proven to be extendable beyond thermodynamics and enhanceable by integrating them with other concepts and ideas. Various types of “thermoeconomic”  
analysis have been applied by authors to integrate exergy and economic analyses (Evans, 1980; Gaggioli and Wepfer, 1980). Later, Tsatsaronis  
and Winhold (1985) used the term “exergoeconomics” to present a more conceptual combination of exergy analysis with economic principles, while Rosen and Dincer (2003)  
developed the exergy–cost–energy–mass (EXCEM) method for the analysis of thermal systems and processes.  

In an attempt to combine exergy analysis with ecological aspects of energy systems, Szargut (1978) proposed the cumulative exergy  
consumption (CExC) approach. “Ecological cost” and “thermoecological cost” indicators were developed by Szargut et al. (2002)  
and Szargut (2004), respectively, on the basis of CExC concept. The CExC method was also enhanced and extended to “exergoenvironmental”  
analysis by Valero et al. (1986) and to extended exergy accounting (EEA) by Scuizza (2001). Frangopolous and Caralis (1997) incorporated external costs caused by  
pollutants in exergoeconomic computations to develop a method called “environmental exergoeconomics”. Several other approaches such as  
exergoeconomic life cycle analysis (Cornelissen, 1997), life cycle exergy analysis (Gong and Wall, 1997), and exergy-based life cycle assessment (Dewulf et al.,  
2000; Dewulf and Van Langenhove, 2002) have continued efforts to combine exergy concepts and environmental assessments. Meyers et al. (2009)  
introduced “exergoenvironmental” analysis by substituting the ecological impact (Eco-indicator 99) for the economic term in the exergoeconomic approach. Khajehpour et al.  
(2017) extended the utilization of exergoenvironmental analysis for macro-level energy systems by taking into account non-energy  
streams. Recently, Aghbashlo and Rosen (2018) substituted the solar energy joule (sej) for the monetary term and environmental  


![Nomenclature](image)

![Fig. 1. Relation between exergy efficiency of an energy system with its sustainability and environmental (including ecological) facets (Dincer and Rosen, 2005).](image)
impact score in the conventional exergoeconomic and exergoenvironmental analyses, respectively. Using these methods, the dimension and scale of both exergoeconomic and exergoenvironmental analyses can be conceptually harmonized. In addition, data emerging from these methods not only can be quickly interpreted by engineers and designers but also can be easily bridged by mathematical techniques.

Overall, exergoeconomic and exergoenvironmental analyses appear to be increasingly popular engineering approaches for component-level analysis, design, and retrofitting energy conversion systems from exergy/economic and exergy/environmental/ecological viewpoints, respectively. This could be ascribed to their unique and practical integration of thermodynamic concepts with economic and environmental/ecological aspects of energy systems. Numerous examples can be found in the literature where exergoeconomic and exergoenvironmental analyses have been used for analyzing, optimizing, and improving energy conversion systems (Orhan et al., 2010; Waheed et al., 2014).

In addition to the standard formulation developed for exergy-based analyses, Tsatsaronis and Morosuk (2008a, 2008b) further enhanced the quality of the conclusions obtained from exergy, exergoeconomic, and exergoenvironmental analyses by splitting the energy destruction as well as its related costs and environmental impacts into endogenous/exogenous and avoidable/unavoidable parts. The so-called advanced exergy-based methods have then been applied in numerous studies to assess interactions among components of energy systems (Boyano et al., 2012; Petrakopoulou et al., 2012).

Although exergoeconomic and exergoenvironmental analyses have been demonstrated to be effective and reliable for analyzing energy systems compared with other exergy-based methods (Aghbashlo and Rosen, 2018), these approaches have been formulated separately from each other. This means that decision-making with respect to exergoeconomic analysis might result in misleading conclusions since it evaluates the systems under consideration on the basis of thermodynamic and economic viewpoints while such outcomes might not meet the environmental goals provided by exergoenvironmental analysis, and vice versa. Therefore, the interconnection between exergoeconomic and exergoenvironmental approaches needs to be established by developing a new tool to aid process design according to enhanced thermodynamic, economic, and environmental performance simultaneously (Meyer et al., 2009). In line with this need, Caliskan (2015a, 2015b, 2017) proposed “exergoenvironmental” (EXEN) and “exergoenvironconomic” (EXENEC) concepts and claimed that these indicators concurrently assess energy systems from environmental, economic, and thermodynamic perspectives. The results of applying these concepts suggest that both concepts exhibit similar trends. Moreover, they only consider the ecological cost of CO₂ emissions or its total equivalent in the proposed indicators. This is a significant limitation since the ecological cost of CO₂ emissions is a portion of the overall eco-costs caused by a system during its lifetime and, more importantly, there is no direct correlation between eco-costs and total equivalent CO₂ emissions. Overall, this exergoenvironconomic approach can only represent the ecological impacts of energy systems in economic terms and does not integrate economic aspects of the system under consideration in its framework.

To the best of authors’ knowledge, there appears to be no single comprehensive framework or metric available to simultaneously evaluate energy conversion systems thermodynamically, economically, and environmentally. Accordingly, this paper aims at developing a new methodology called “exergoenvironconomic” analysis, so as to provide a better understanding of energy conversion systems from thermodynamic, economic, and environmental points of view simultaneously. This approach is applied to a well-known gas turbine-based cogeneration system as an example to demonstrate how exergoenvironeconomic analysis enables the investigation of energy systems at a component-level strategy. The developed approach is expected to contribute to an enhanced understanding of energy conversion systems thermodynamically, economically, and environmentally.

2. Theoretical considerations

2.1. Concept

Fig. 2 illustrates the detailed implementation procedure of exergoenvironconomic analysis introduced throughout this study. According to this Figure, the implementation procedure of this method can be summarized as follows:

1) Define goal and scope
2) Model the energy conversion system
3) Carry out exergy analysis
4) Perform exergy cost analysis
5) Calculate eco-costs
6) Determine eco-costs/value ratio
7) Assign eco-costs/value ratio to the unit exergetic cost of streams
8) Compute exergoenvironeconomic variables
9) Conduct exergoenvironeconomic evaluation
10) Find improved option

The eco-costs/value ratio concept is thoroughly explained in subsection 2.4. Accordingly, exergoenvironeconomic variables are determined and an exergoenvironconomic assessment is conducted. Generally, the obtained results identify the most important components having the highest eco-costs/value ratio. All the above-mentioned steps required for an exergoenvironeconomic analysis are comprehensively elaborated and discussed in the following subsections.

2.2. Exergy analysis

After defining the boundaries of the system under consideration and the components involved, the exergy of all material and energy streams is quantified. The definition of exergy of product (ExP_k) and fuel (ExF_k) is then applied to characterize each component of the system according to the SPECO approach. Accordingly, the exergy efficiency, exergy destruction rate, and exergy destruction ratio can be computed for each component of the system. By neglecting heat transfer to the environment, the exergy rate balance for the k-th component of an energy conversion system can be written as follows:

\[ \dot{E}_{xF,k} = \dot{E}_{XP,k} + \dot{E}_{XD,k} \]  

Using the exergy rate balance equation, the exergy destruction rate within the k-th component (ExD_k) can be computed. The exergy efficiency of k-th component (\( \varepsilon_k \)) can be obtained as

\[ \varepsilon_k = \frac{\dot{E}_{XP,k}}{\dot{E}_{xF,k}} = 1 - \frac{\dot{E}_{XD,k}}{\dot{E}_{xF,k}} \]  

In order to rank the components of an energy conversion system according to their contribution to the overall exergy destruction, the exergy destruction ratio is defined as follows:
2.3. Exergetic cost analysis

The exergetic cost of a given flow (material or energy) represents the quantity of exergy required for its production. Similarly, the dimensionless unit exergetic cost is the quantity of exergy needed to produce a unit of exergy of a material or energy stream (Lozano and Valero, 1993). Therefore, the unit average exergetic cost \( k_i \) of each exergy stream can be expressed as follows:

\[
k_i = \frac{\dot{E}_{x_i}}{\dot{E}_{x_i}^*}
\]

where \( \dot{E}_{x_i} \) and \( \dot{E}_{x_i}^* \) are the exergy and the exergetic cost of the \( i \)-th stream, respectively. Readers are referred to Lozano and Valero (1993) and Valero et al. (2004) for further information on exergetic cost theory. The unit exergetic cost of each exergy stream is the summation of the unit exergetic cost due to irreversibilities \( k_{i,e} \) and residues \( k_{i,r} \) (Torres et al., 2008). That is,

\[
k_i = k_{i,e} + k_{i,r}
\]

Similarly, the unit exergetic production cost of the \( k \)-th component is decomposed into two parts viz. the unit exergetic production costs due to irreversibilities \( k_{k,e} \) and residues \( k_{k,r} \):

\[
k_k = k_{k,e} + k_{k,r}
\]

Note that thermoeconomic analysis can be straightforwardly and conveniently carried out with TAESS free-software available at http://www.exergoeconomy.com/. This software was developed by Torres et al. (2012) for the thermoeconomic analysis of energy conversion systems.

2.4. Eco-costs/value ratio

The eco-costs/value ratio concept was introduced in 2000 by Vogtländer and Bijma to attain two aims simultaneously, i.e., sustainability and economy as part of LCA studies (Vogtländer and Bijma, 2000). The eco-costs represent the virtual prevention costs of environmental burden of a product, while the value shows its actual price or cost in the free market economy. This concept has been comprehensively elaborated in a series of works by Vogtländer et al. (2002, 2001). The main idea behind this concept is that the product having the lowest eco-cost (or in terms of milli-points/carbon footprint) is not often the best choice for sustainability. However, the dimensionless eco-costs/value ratio can reflect well sustainability by linking economy and ecology into a single framework.

Eco-costs indicate that marginal costs should be spent to discount the environmental pollution and materials depletion to a sustainable level. The eco-costs are determined at two levels, i.e., eleven midpoint eco-costs and four endpoint eco-costs (http://www.ecocostsvalue.com/). The endpoint eco-costs include the eco-costs of human health, ecosystem health, resource depletion, and global warming (Fig. 3). The midpoint eco-costs consist of the eco-cost of carcinogens, summer smog, fine dust (eco-costs of human health), acidification, eutrophication, ecotoxicity (eco-costs of ecosystems), abiotic depletion, land-use, water and land-fill (eco-costs of resource depletion), \( CO_2 \) and other greenhouse gases (eco-costs of global warming). To improve understanding, some eco-cost values of the above-mentioned midpoints are tabulated in Table 1. The newly updated version of eco-costs for various materials can be found from http://www.ecocostsvalue.com/.
2.5. Exergoeconoenvironmental evaluation

Assignment of the results of eco-costs/value ratio analysis to the unit exergetic cost of streams is carried out in a manner analogous to the assignment of cost and environmental impact to exergy streams in exergoeconomic and exergoenvironmental analyses, respectively (Bejan et al., 1996; Meyer et al., 2009). An eco-costs/value ratio $A_i$ and an eco-costs/value per unit exergetic cost $a_i$ are introduced. The eco-costs/value ratio $A_i$ is the ratio of virtual pollution prevention costs to the actual cost (USD eco-costs/USD value). The specific eco-costs/value ratio $a_i$ is the average eco-costs/value ratio associated with the production of the $i$-th exergy stream per unit exergetic cost of the same stream (USD eco-costs/MW/USD value MW). The eco-costs/value ratio $A_i$ of the $i$-th stream is the product of its unit exergetic cost $k_i$ and the specific eco-costs/value ratio $a_i$:

$$A_i = a_i k_i$$

Unlike exergoeconomic and exergoenvironmental analyses, the dimensionless unit exergetic cost (MW/MW) is used in the exergoeconoenvironmental analysis in order to make its balance dimensionless.

Moreover, the eco-cost/value ratio associated with heat $Q$ and work $W$ transfers are computed using the following equations:

$$A_Q = a_Q k_Q$$

$$A_W = a_W k_W$$

An exergoeconoenvironmental balance for each component of the system can be written as

$$A_{P,k} = A_{F,k} + X_k$$

$$a_{P,k} k_{P,k} = a_{F,k} k_{F,k} + X_k$$

Since the unit exergetic cost of input streams, i.e., fuel streams entering the overall system is equal to 1 according to thermo-economic analysis, their specific eco-costs/value ratio is equal to eco-costs/value ratio. In addition to the eco-costs/value ratio of fuel streams, the component-related eco-costs/value ratio $X_k$ (USD eco-costs/USD value) associated with the life cycle of the $k$-th component are determined:

$$X_k = \frac{X_{k}^{CO} + X_{k}^{OM} + X_{k}^{DI}}{2}$$

where $X_{k}^{CO}$ is the eco-costs associated with the construction phase (including manufacturing, transport and installation), $X_{k}^{OM}$ denotes the eco-costs associated with pollutants emitted during operation and maintenance, and $X_{k}^{DI}$ represents the eco-costs associated with disposal or recycling of materials used in the construction phase. Based on the assumptions implied by Petrakopoulou et al. (2011), the design and construction stages can be taken into account and examined as the main phases of the plant components.

After writing the exergoeconoenvironmental balance for each component of the system, auxiliary equations can be obtained using F and P principles similar to exergoeconomic and exergoenvironmental analyses (Lazzaretto and Tsatsaronis, 2006; Meyer et al., 2009). Moreover, dissipative components can be treated using the methodology comprehensively elaborated in Lazzaretto and Tsatsaronis (2006) and Meyer et al. (2009).

2.6. Exergoeconoenvironmental variables

Similar to the exergy, exergoeconomic, and exergoenvironmental analyses, specific eco-costs/value ratio of fuel and product for the $k$-th component can be obtained as follows:

$$a_{P,k} = \frac{A_{P,k}}{k_{P,k}}$$

$$a_{F,k} = \frac{A_{F,k}}{k_{F,k}}$$

The eco-costs/value ratio associated with the thermodynamic irreversibility within $k$-th component ($A_{D,k}$) can be determined as follows:

$$A_{D,k} = a_{F,k} k_{k,e}$$

where $k_{k,e}$ is the unit exergetic production cost of $k$-th component due to irreversibilities (MW/MW) obtained by using the thermo-economic analysis explained previously.

Total eco-costs/value ratio associated with a component can be obtained as the summation of the eco-costs/value ratio associated with the $k$-th component and its exergy destruction as follows:

$$A_{TOT,k} = X_k + A_{D,k}$$

The relative eco-costs/value ratio difference $r_{a,k}$ between the average eco-costs/value ratio of the product $a_{F,k}$ and the fuel $a_{F,k}$ can be expressed as

Table 1

<table>
<thead>
<tr>
<th>Selected eco-costs midpoint values (<a href="http://www.ecocostsvalue.com">http://www.ecocostsvalue.com</a>)</th>
<th>Category</th>
<th>Multiplier (marginal prevention costs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-costs of acidification</td>
<td>10.73 USD/kg S0x equivalent</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of eutrophication</td>
<td>5.07 USD/kg phosphate equivalent</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of ecotoxicity</td>
<td>71.50 USD/kg Zn equivalent</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of human toxicity</td>
<td>46.80 USD/kg Benzo(a)pyrene equivalent</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of summer smog (respiratory diseases)</td>
<td>12.61 USD/kg C2H4 equivalent</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of fine dust</td>
<td>44.20 USD/kg fine dust PM2.5</td>
<td></td>
</tr>
<tr>
<td>Eco-costs of global warming</td>
<td>0.18 USD/kg CO2 equivalent (GWP 100)</td>
<td></td>
</tr>
</tbody>
</table>
\[ r_{a,k} = \frac{a_{p,k} - a_{F,k}}{a_{F,k}} \]  

(17)

The exergoeconomic factor \( f_{a,k} \) can be computed as the relative contribution of the component-related eco-costs/value ratio to the sum of eco-costs/value ratio associated with the \( k \)-th component as follows:

\[ f_{a,k} = \frac{X_k}{X_k + A_{D,k}} = \frac{X_k}{A_{TOT,k}} \]  

(18)

3. Case study

As an example, the developed concept is applied to a typical gas turbine-based cogeneration system (Fig. 4). This system consists of an air compressor (AC), a combustion chamber (CC), a gas turbine (GT), an air preheater (APH), and a heat-recovery steam generator (HRSG).

3.1. Exergy analysis

The exergy balance equation and exergy efficiency of each component of the cogeneration system are given below.

For AC:

\[ \dot{E}_X + \dot{E}_{X11} - \dot{E}_{X2} = \dot{E}_{D,AC} \]  

(19)

\[ \epsilon_{AC} = \frac{\dot{E}_{X2} - \dot{E}_{X1}}{\dot{E}_{X11}} \]  

(20)

For APH:

\[ \left( \dot{E}_{X5} - \dot{E}_{X6} \right) - \left( \dot{E}_{X3} - \dot{E}_{X2} \right) = \dot{E}_{D,APH} \]  

(21)

\[ \epsilon_{APH} = \frac{\dot{E}_{X3} - \dot{E}_{X2}}{\dot{E}_{X5} - \dot{E}_{X6}} \]  

(22)

For CC:

\[ \dot{E}_{X3} + \dot{E}_{X10} - \dot{E}_{X4} = \dot{E}_{D,CC} \]  

(23)

For GT:

\[ \dot{E}_{X4} - \dot{E}_{X3} = \dot{E}_{D,GT} \]  

(24)

For HRSG:

\[ \dot{E}_{X5} - \dot{E}_{X7} = \dot{E}_{D,HRSG} \]  

(25)

3.2. Exergoeconomic analysis

The cost balance and auxiliary equation(s) of each component of the cogeneration system are given below.

For AC:

\[ c_{11} \dot{E}_{X11} + \dot{Z}_{AC} = c_2 \dot{E}_{X2} - c_1 \dot{E}_1 \]  

(29)

For APH:

\[ c_5 \dot{E}_{X5} - c_6 \dot{E}_{X6} + \dot{Z}_{APH} = c_3 \dot{E}_{X3} - c_2 \dot{E}_{X2} \]  

(30)

For CC:

\[ c_{10} \dot{E}_{X10} + \dot{Z}_{CC} = c_4 \dot{E}_{X4} - c_3 \dot{E}_{X3} \]  

(31)

For GT:

\[ c_4 \dot{E}_{X4} - c_5 \dot{E}_{X5} + \dot{Z}_{GT} = c_{11} \dot{E}_{X11} + c_{12} \dot{E}_{X12} \]  

(32)

For HRSG:

\[ c_6 \dot{E}_{X6} - c_7 \dot{E}_{X7} + \dot{Z}_{HRSG} = c_8 \dot{E}_{X9} - c_8 \dot{E}_{X8} \]  

(33)

The relative cost difference \( r_{c,k} \) between the average cost of the product \( c_{p,k} \) and the fuel \( c_{F,k} \) can be obtained as follows:

\[ r_{c,k} = \frac{c_{p,k} - c_{F,k}}{c_{F,k}} \]  

(34)

The exergoeconomic factor \( f_{c,k} \) can be determined as the relative contribution of the component-related cost to the sum of costs associated with the \( k \)-th component as

\[ f_{c,k} = \frac{\dot{Z}_k}{\dot{Z}_k + c_F \dot{E}_{D,k}} \]  

(35)

Fig. 4. Gas turbine-based cogeneration system.
3.3. Exergoenvironmental analysis

The environmental impact balance and auxiliary equation(s) of each component of the cogeneration system are given below.

For AC:

\[ b_{11} \dot{E}_{11} + \dot{Y}_{AC} = b_2 \dot{E}_2 - b_1 \dot{E}_1 \]
\[ b_1 = 0 \]  \hspace{1cm} (36)

For APH:

\[ (b_3 \dot{E}_3 - b_6 \dot{E}_6) + \dot{Y}_{APH} = b_3 \dot{E}_3 - b_2 \dot{E}_2 \]
\[ b_5 = b_6 \text{(F rule)} \]  \hspace{1cm} (37)

For CC:

\[ b_{10} \dot{E}_{10} + \dot{Y}_{CC} = b_4 \dot{E}_4 - b_3 \dot{E}_3 \]
\[ b_{10} = 5114.983 \text{ mPt} / \text{GJ} \]  \hspace{1cm} (38)

For GT:

\[ (b_4 \dot{E}_4 - b_5 \dot{E}_5) + \dot{Y}_{GT} = b_{11} \dot{E}_{11} + b_{12} \dot{E}_{12} \]
\[ b_4 = b_5 \text{(F rule)} \]
\[ b_{11} = b_{12} \text{(P rule)} \]  \hspace{1cm} (39)

For HRSG:

\[ (b_6 \dot{E}_6 - b_7 \dot{E}_7) + \dot{Y}_{HRSG} = b_9 \dot{E}_9 - b_8 \dot{E}_8 \]
\[ b_6 = b_7 \text{(F rule)} \]
\[ b_8 = 0 \text{(arbitrary assumption)} \]  \hspace{1cm} (40)

The relative environmental impact difference \( r_{b,k} \) between the average cost of the product \( b_{p,k} \) and the fuel \( b_{f,k} \) can be obtained as follows:

\[ r_{b,k} = \frac{b_{p,k} - b_{f,k}}{b_{f,k}} \]  \hspace{1cm} (41)

The exergoenvironmental factor \( f_{b,k} \) can be computed as the relative contribution of the component-related environmental impact to the sum of environmental impacts associated with the \( k \)-th component as follows:

\[ f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + b_f \dot{E}_{D,k}} \]  \hspace{1cm} (42)

3.4. Exergoeconoenvironmental analysis

The econoenvironmental balance and auxiliary equation(s) of each component of the cogeneration system are given below:

For AC:

\[ a_{11} k_{11} + X_{AC} = a_2 k_2 - a_1 k_1 \]
\[ a_1 = 0 \]  \hspace{1cm} (43)

For APH:

\[ (a_3 k_5 - a_8 k_8) + X_{APH} = a_3 k_3 - a_2 k_2 \]
\[ a_5 = a_6 \text{(F rule)} \]  \hspace{1cm} (44)

For CC:

\[ a_{10} k_{10} + X_{CC} = a_4 k_4 - a_3 k_3 \]
\[ a_{10} = 2.519 \text{ (USD eco - costs/USD value)} \]  \hspace{1cm} (45)

For GT:

\[ (a_4 k_4 - a_9 k_9) + X_{GT} = a_{11} k_{11} + a_{12} k_{12} \]
\[ a_4 = a_9 \text{(F rule)} \]
\[ a_{11} = a_{12} \text{(P rule)} \]  \hspace{1cm} (46)

For HRSG:

\[ (a_6 k_6 - a_7 k_7) + X_{HRSG} = a_9 k_9 - a_8 k_8 \]
\[ a_6 = a_7 \text{(F rule)} \]
\[ a_8 = 0 \text{(arbitrary assumption)} \]  \hspace{1cm} (47)

3.5. Data used in exergoeconomic, exergoenvironmental, and exergoeconoenvironmental analyses

Table 2 lists data used in the exergoeconomic, exergoenvironmental, and exergoeconoenvironmental analyses of the gas turbine-based cogeneration system. These data are obtained from Tsatsaronis and Morosuk (2008b) and http://www.ecocostsvalue.com/. The required economic (monetary) values as well as the type and quantity of materials used in the construction of the plant components are obtained from Tsatsaronis and Morosuk (2008a). It is emphasized that the goal of this work is to propose and apply a general method for exergoeconoenvironmental analysis of energy conversion systems at the component-level strategy. The users can carry out exergoeconoenvironmental analysis for their own cases using actual and precise databases. The ReCiPe (RIVM and Radboud University, CML, and PRé Consultants) indicator is used throughout this study as it constitutes one of the most recent and harmonized methods developed in life cycle impact assessment domain. Moreover, the eco-cost values are computed using data obtained from http://www.ecocostsvalue.com/. The lifetime of the plant is considered to be 20 years with 7446 working hours per year.

4. Results and discussion

Table 3 summarizes the stream type, mass flow rate, temperature, pressure, specific exergy, and exergy rate of all streams shown in Fig. 3. The plant produces two products viz. 30 MW net mechanical power and 14 kg/s of saturated water vapor at a pressure of 20 bar. The exergy rates associated with these streams are determined to be 30.0 MW and 12.8 MW, respectively.

Table 4 lists the exergy costs of all streams of the gas turbine-based cogeneration system. Note that a virtual stack (dissipative component) is considered for the combustion gas leaving the system (stream 7) in order to calculate the exergetic cost due to residue. Unlike the unit monetary cost or exergoeconomic cost (USD/GJ) as reported in Table 6, the unit exergy cost (MW/GJ) is the amount of exergy required to produce a mass or energy stream of an energy flow. The saturated steam (stream 9) has the highest overall unit exergetic cost, manifesting the fact that a large quantity of exergy is required for its production. This can be ascribed to the intense heat and mass transfer as well as the rapid phase change during the water evaporation process. The contribution of irreversibilities to the overall unit exergetic cost of net mechanical power and saturated water vapor as products of the system is found to be 94.75% and 94.83%, while the residue accounts for 5.25% and 5.17% of the overall unit exergetic cost of these streams, respectively. This means that the irreversibilities make the main contributions to the overall unit exergetic costs of product streams.

Table 5 gives the exergy costs of all components of the gas turbine-based cogeneration system. The highest overall unit exergetic production cost is attributable to the HRSG unit due to the higher overall unit exergetic cost of saturated steam, as discussed previously. The lowest overall unit exergetic production cost is determined to be 1.770 MW/MW for the GT unit. The contribution of irreversibilities to the overall unit exergetic production cost of
the HRSG unit is found to be 94.74%. This means that the exergetic performance of the HRSG can be greatly improved by reducing or minimizing the irreversibilities. The contribution of residue to the overall unit exergetic production cost of the plant components is found to be in the range of 5.22%–5.26%. In general, residue only accounts for a little (<6%) of the overall unit exergetic production cost of the system units.

Table 6 provides economic, environmental, and economoenvironmental data for the cogeneration system. The specific costs of the net mechanical power and saturated steam as the products of the plant are found to be 18.77 USD/GJ and 27.20 USD/GJ, respectively, while the specific environmental impacts of these streams are determined to be 8.58 × 10^4 mPts/GJ and 104 mPts/GJ, respectively. The highest specific cost (27.77 USD/GJ) occurs for compressed air leaving the AC unit. However, the saturated steam has the highest specific environmental impact (104 mPts/GJ). The results also indicate that the supply of natural gas to the plant has the highest specific exergy costs of the net mechanical power and saturated steam as (1.21 × 10^4 USD/MW) and (1.10 × 10^4 USD/MW, respectively.

Table 2
Data used in exergoeconomic, exergoenvironmental, and exergoeconoenvironmental analyses of the cogeneration system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>ReCiPe indicator (mPts/kg)</th>
<th>Eco-cost (USD/kg)</th>
<th>Amount of material (kg)</th>
<th>Points (mPts)</th>
<th>Eco-cost (USD)</th>
<th>Value (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Steel</td>
<td>220.348</td>
<td>0.623</td>
<td>4612</td>
<td>1.016 × 10^6</td>
<td>2.87 × 10^3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel low alloy</td>
<td>246.029</td>
<td>0.663</td>
<td>6150</td>
<td>1.51 × 10^6</td>
<td>4.08 × 10^3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cast iron</td>
<td>86.316</td>
<td>0.254</td>
<td>3075</td>
<td>2.654 × 10^5</td>
<td>7.83 × 10^2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.79 × 10^4</td>
<td>7.73 × 10^2</td>
<td>3.73 × 10^4</td>
</tr>
<tr>
<td>APH</td>
<td>Steel</td>
<td>220.348</td>
<td>0.623</td>
<td>16800</td>
<td>3.70 × 10^4</td>
<td>1.05 × 10^4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cast iron</td>
<td>86.316</td>
<td>0.254</td>
<td>84000</td>
<td>7.3 × 10^6</td>
<td>2.1 × 10^4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.1 × 10^7</td>
<td>3.2 × 10^4</td>
<td>9.40 × 10^4</td>
</tr>
<tr>
<td>CC</td>
<td>Steel</td>
<td>220.348</td>
<td>0.623</td>
<td>1538</td>
<td>3.389 × 10^3</td>
<td>9.59 × 10^2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel high alloy</td>
<td>550.221</td>
<td>3.708</td>
<td>3075</td>
<td>1.692 × 10^5</td>
<td>1.140 × 10^4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.031 × 10^6</td>
<td>1.24 × 10^4</td>
<td>3.40 × 10^4</td>
</tr>
<tr>
<td>GT</td>
<td>Steel</td>
<td>220.348</td>
<td>0.623</td>
<td>3075</td>
<td>6.776 × 10^4</td>
<td>1.92 × 10^3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel high alloy</td>
<td>550.221</td>
<td>3.708</td>
<td>9225</td>
<td>5.078 × 10^4</td>
<td>1.320 × 10^4</td>
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</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.753 × 10^6</td>
<td>3.61 × 10^4</td>
<td>3.74 × 10^4</td>
</tr>
<tr>
<td>HRSG</td>
<td>Steel</td>
<td>220.348</td>
<td>0.623</td>
<td>17000</td>
<td>3.7 × 10^6</td>
<td>1.1 × 10^4</td>
<td></td>
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<tr>
<td></td>
<td>Cast iron</td>
<td>86.316</td>
<td>0.254</td>
<td>68000</td>
<td>5.9 × 10^6</td>
<td>1.7 × 10^4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td>9.6 × 10^6</td>
<td>2.8 × 10^4</td>
<td>1.31 × 10^5</td>
</tr>
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</table>

Table 3
Stream type, mass flow rate, temperature, pressure, specific exergy, and exergy rate of all streams of the cogeneration system.

<table>
<thead>
<tr>
<th>No.</th>
<th>Stream type</th>
<th>Mass flow rate (kg/s)</th>
<th>Temperature (K)</th>
<th>Pressure (bar)</th>
<th>Specific exergy (MJ/kg)</th>
<th>Exergy rate (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>91.28</td>
<td>298.1</td>
<td>1.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>Air</td>
<td>91.28</td>
<td>603.7</td>
<td>10.13</td>
<td>0.302</td>
<td>27.6</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>91.28</td>
<td>850</td>
<td>9.62</td>
<td>0.459</td>
<td>41.9</td>
</tr>
<tr>
<td>4</td>
<td>Combustion gas</td>
<td>92.92</td>
<td>1520</td>
<td>9.14</td>
<td>1.092</td>
<td>101.5</td>
</tr>
<tr>
<td>5</td>
<td>Combustion gas</td>
<td>92.92</td>
<td>1006.2</td>
<td>1.1</td>
<td>0.417</td>
<td>38.7</td>
</tr>
<tr>
<td>6</td>
<td>Combustion gas</td>
<td>92.92</td>
<td>779.8</td>
<td>1.07</td>
<td>0.234</td>
<td>21.7</td>
</tr>
<tr>
<td>7</td>
<td>Combustion gas</td>
<td>92.92</td>
<td>426.9</td>
<td>1.01</td>
<td>0.03</td>
<td>2.8</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>14</td>
<td>298.1</td>
<td>20</td>
<td>0.04</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>Saturated steam</td>
<td>14</td>
<td>485.6</td>
<td>20</td>
<td>0.915</td>
<td>12.8</td>
</tr>
<tr>
<td>10</td>
<td>Natural gas</td>
<td>1.64</td>
<td>298.1</td>
<td>12</td>
<td>51.825</td>
<td>85.0</td>
</tr>
<tr>
<td>11</td>
<td>Power to AC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29.66</td>
</tr>
<tr>
<td>12</td>
<td>Net power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30.00</td>
</tr>
</tbody>
</table>

Table 4
Exergy cost analysis of all streams of the cogeneration system.

<table>
<thead>
<tr>
<th>No.</th>
<th>Stream type</th>
<th>Unit exergetic cost due to irreversibilities (MW/MW)</th>
<th>Unit exergetic cost due to residue (MW/MW)</th>
<th>Overall unit exergetic cost (MW/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>Air</td>
<td>1.804</td>
<td>0.100</td>
<td>1.904</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>1.835</td>
<td>0.101</td>
<td>1.936</td>
</tr>
<tr>
<td>4</td>
<td>Combustion gas</td>
<td>1.595</td>
<td>0.088</td>
<td>1.683</td>
</tr>
<tr>
<td>5</td>
<td>Combustion gas</td>
<td>1.595</td>
<td>0.088</td>
<td>1.683</td>
</tr>
<tr>
<td>6</td>
<td>Combustion gas</td>
<td>1.595</td>
<td>0.088</td>
<td>1.683</td>
</tr>
<tr>
<td>7</td>
<td>Combustion gas</td>
<td>1.595</td>
<td>0.088</td>
<td>1.683</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>1.000</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>9</td>
<td>Saturated steam</td>
<td>2.404</td>
<td>0.130</td>
<td>2.535</td>
</tr>
<tr>
<td>10</td>
<td>Natural gas</td>
<td>1.000</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>11</td>
<td>Power to AC</td>
<td>1.677</td>
<td>0.093</td>
<td>1.770</td>
</tr>
<tr>
<td>12</td>
<td>Net power</td>
<td>1.677</td>
<td>0.093</td>
<td>1.770</td>
</tr>
</tbody>
</table>

Table 5
Exergy costs of all components of the cogeneration system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit exergetic production cost due to irreversibilities (MW/MW)</th>
<th>Unit exergetic production cost due to residue (MW/MW)</th>
<th>Overall unit exergetic production cost (MW/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>1.804</td>
<td>0.100</td>
<td>1.904</td>
</tr>
<tr>
<td>APH</td>
<td>1.893</td>
<td>0.105</td>
<td>1.997</td>
</tr>
<tr>
<td>CC</td>
<td>1.595</td>
<td>0.088</td>
<td>1.683</td>
</tr>
<tr>
<td>GT</td>
<td>1.677</td>
<td>0.093</td>
<td>1.770</td>
</tr>
<tr>
<td>HRSG</td>
<td>2.468</td>
<td>0.136</td>
<td>2.605</td>
</tr>
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Table 6
Economic, environmental, and excono-evironmental data for the cogeneration system.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>Air</td>
<td>2756</td>
<td>27.77</td>
<td>9.16 x 10^5</td>
<td>9.23 x 10^3</td>
</tr>
<tr>
<td>3</td>
<td>Air</td>
<td>3833</td>
<td>25.42</td>
<td>1.42 x 10^6</td>
<td>9.39 x 10^4</td>
</tr>
<tr>
<td>4</td>
<td>Combustion gas</td>
<td>5301</td>
<td>14.51</td>
<td>2.98 x 10^2</td>
<td>8.16 x 10^3</td>
</tr>
<tr>
<td>5</td>
<td>Combustion gas</td>
<td>2024</td>
<td>14.51</td>
<td>1.14 x 10^4</td>
<td>8.16 x 10^3</td>
</tr>
<tr>
<td>6</td>
<td>Combustion gas</td>
<td>1136</td>
<td>14.51</td>
<td>6.39 x 10^4</td>
<td>8.16 x 10^3</td>
</tr>
<tr>
<td>7</td>
<td>Combustion gas</td>
<td>145.6</td>
<td>14.51</td>
<td>18.19 x 10^4</td>
<td>8.16 x 10^3</td>
</tr>
<tr>
<td>8</td>
<td>Water</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>Saturated steam</td>
<td>1254</td>
<td>27.20</td>
<td>5.57 x 10^2</td>
<td>1.21 x 10^4</td>
</tr>
<tr>
<td>10</td>
<td>Natural gas</td>
<td>1398</td>
<td>4.570</td>
<td>1.57 x 10^5</td>
<td>5.11 x 10^4</td>
</tr>
<tr>
<td>11</td>
<td>Power to air compressor</td>
<td>2004</td>
<td>18.77</td>
<td>9.16 x 10^3</td>
<td>8.58 x 10^3</td>
</tr>
<tr>
<td>12</td>
<td>Net power</td>
<td>2027</td>
<td>18.77</td>
<td>9.26 x 10^3</td>
<td>8.58 x 10^3</td>
</tr>
</tbody>
</table>

Tables 7–10 provide the outcomes of the exergy, exergoeconomic, exergoenvironmetrical, and exergoeconoenvironmental analyses, respectively. Figs. 5–8 also present Sankey diagrams for the exergy, exergoeconomic, exergoenvironmental, and exergoeconoenvironmental analyses of the gas turbine-based cogeneration system. Based on the results in Table 7, the total exergy destruction rate of the plant is equal to 42.25 MW.

Table 7
Results of exergy analysis of the cogeneration system.

<table>
<thead>
<tr>
<th>Component</th>
<th>E_{ex} (MW)</th>
<th>E_{eax} (MW)</th>
<th>E_{oex} (MW)</th>
<th>y_{ex} (%)</th>
<th>Improvement priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>29.66</td>
<td>27.57</td>
<td>2.10</td>
<td>92.94</td>
<td>2.47</td>
</tr>
<tr>
<td>APH</td>
<td>66.31</td>
<td>63.64</td>
<td>2.67</td>
<td>84.28</td>
<td>3.15</td>
</tr>
<tr>
<td>CC</td>
<td>126.9</td>
<td>101.5</td>
<td>25.42</td>
<td>79.97</td>
<td>29.91</td>
</tr>
<tr>
<td>GT</td>
<td>101.5</td>
<td>98.41</td>
<td>3.06</td>
<td>96.99</td>
<td>3.60</td>
</tr>
<tr>
<td>HRSG</td>
<td>22.30</td>
<td>15.60</td>
<td>6.71</td>
<td>64.62</td>
<td>7.89</td>
</tr>
</tbody>
</table>

Table 8
Results of exergoeconomic analysis of the cogeneration system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Z_{A} (USD/h)</th>
<th>C_{A_{D}} (USD/h)</th>
<th>Z_{A} + C_{D_{A}} (USD/h)</th>
<th>C_{P_{A}} (USD/GJ)</th>
<th>C_{P_{A}} (USD/GJ)</th>
<th>r_{A_{k}} (%)</th>
<th>f_{A_{k}} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>752.1</td>
<td>141.6</td>
<td>893.7</td>
<td>18.77</td>
<td>27.77</td>
<td>47.98</td>
<td>84.16</td>
</tr>
<tr>
<td>APH</td>
<td>189.5</td>
<td>139.7</td>
<td>329.2</td>
<td>14.51</td>
<td>20.89</td>
<td>43.98</td>
<td>57.58</td>
</tr>
<tr>
<td>CC</td>
<td>68.6</td>
<td>1048</td>
<td>1117</td>
<td>14.51</td>
<td>14.51</td>
<td>26.69</td>
<td>61.4</td>
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<tr>
<td>GT</td>
<td>754.2</td>
<td>159.8</td>
<td>914.0</td>
<td>14.51</td>
<td>14.51</td>
<td>29.33</td>
<td>82.52</td>
</tr>
<tr>
<td>HRSG</td>
<td>264.2</td>
<td>350.3</td>
<td>614.5</td>
<td>14.51</td>
<td>28.45</td>
<td>96.02</td>
<td>42.99</td>
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Table 9
Results of exergoenvironmental analysis of the cogeneration system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Y_{A} (mPts/h)</th>
<th>B_{D_{A}} (mPts/h)</th>
<th>Y_{A} + B_{D_{A}} (mPts/h)</th>
<th>b_{A_{k}} (mPts/GJ)</th>
<th>b_{A_{k}} (mPts/GJ)</th>
<th>r_{A_{k}} (%)</th>
<th>f_{A_{k}} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>18.77</td>
<td>6.471 x 10^4</td>
<td>6.473 x 10^4</td>
<td>8.578 x 10^3</td>
<td>9.231 x 10^3</td>
<td>7.60</td>
<td>2.9 x 10^-2</td>
</tr>
<tr>
<td>APH</td>
<td>73.55</td>
<td>7.853 x 10^4</td>
<td>7.861 x 10^4</td>
<td>8.160 x 10^3</td>
<td>9.684 x 10^3</td>
<td>18.67</td>
<td>9.4 x 10^-2</td>
</tr>
<tr>
<td>CC</td>
<td>13.64</td>
<td>5.972 x 10^3</td>
<td>5.975 x 10^3</td>
<td>6.525 x 10^3</td>
<td>8.160 x 10^3</td>
<td>25.06</td>
<td>2.0 x 10^-3</td>
</tr>
<tr>
<td>GT</td>
<td>38.63</td>
<td>8.996 x 10^4</td>
<td>8.999 x 10^4</td>
<td>8.160 x 10^3</td>
<td>8.578 x 10^3</td>
<td>5.13</td>
<td>4.3 x 10^-2</td>
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<tr>
<td>HRSG</td>
<td>64.57</td>
<td>1.970 x 10^5</td>
<td>1.970 x 10^5</td>
<td>8.160 x 10^3</td>
<td>1.263 x 10^4</td>
<td>54.76</td>
<td>3.3 x 10^-2</td>
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</table>

The highest value of the exergy destruction rate is attributable to the CC unit, accounting for over 29% of the total exergy destruction rate of the plant. This essentially occurs due to significant heat and mass transfer, irreversible chemical reaction, and significant mixing processes during natural gas combustion. The HRSG unit is responsible for 7.89% of the overall exergy destruction rate of the system. The HRSG has the lowest exergy efficiency (64.62%) owing...
to the fact that a substantial portion of the supplied exergy rate (6.71 MW) is irreversibly destroyed. The second lowest exergy efficiency (79.97%) is observed for the CC unit due to its high exergy destruction rate (25.42 MW). According to the results of exergy analysis, attention should be paid to the CC and HRSG units in order to enhance the overall efficiency of the plant.

According to the results in Table 8, the main contributors to the total cost rate are as follows in descending order of importance: CC, GT, AC, HRSG, and APH. The total cost rate of the CC unit is 1117 USD/h, while this value is found to be 914 USD/h for the GT unit. Overall, it can be concluded that attempts to improve the exergoeconomic performance of the plant should focus on the CC and GT units. In other words, a reduction of the total cost rate can be attained by augmenting the exergetic efficiency of all components, but mainly those of the CC and GT units. However, it should be noted that conventional exergy analysis proposes improvement of the CC and HRSG for enhancing plant performance. This demonstrates how a main outcome of exergy analysis, i.e., exergy destruction rate, might lead to misleading conclusions when analyzing an energy system without taking into account the economic context.

The exergoeconomic factor is calculated to be in the range of 6.14%–84.16% for the plant components (Table 8). It is clear that component-related cost rate is the dominant source for the total cost rate of the AC and GT units, whereas exergy destruction is the dominant source for the total cost rate of the CC unit. Moreover, the total cost rate of the APH and HRSG units is influenced from both component-related and exergy destruction costs. Therefore, economic improvement efforts should be concentrated on reducing or minimizing the thermodynamic irreversibilities of the CC unit and the component-related cost of AC and GT units. The relative cost difference of the plant units ranges from 26.69% to 96.02%. Generally, the relative cost difference reveals the potential for discounting the unit cost of the product. The higher relative cost difference indicates that the unit cost of the product of the corresponding component can be decreased with a smaller effort compared with a component having a lower relative cost difference. Overall, there is little chance to lower the unit cost of the product of the CC unit. However, the unit cost of the product of the HRSG unit can be greatly reduced by minimizing the exergy destruction rate and the component-related cost.

The CC and HRSG units make the largest contributions to the total environmental impact rate of the plant, according to the data in Table 9. The total environmental impact rates of the CC and HRSG units are determined to be $5.972 \times 10^5$ mPts/h and $1.970 \times 10^5$ mPts/h, respectively. Similar to the conventional exergy analysis, the plant performance can be exergoenvironmentally improved if attention is paid to the CC and HRSG units. Even though the first improvement priority of the exergy, exergoeconomic, exergoenvironmental analyses is the CC unit, the second improvement priority of the exergoeconomic analysis is different from that of both other approaches. Overall, the exergoeconomic approach might mislead as it identifies the improvement priority on the basis of the highest total cost rate while such components might not
necessarily have the highest total environmental impact rate and vice versa.

The exergoenvironmental factor of the plant units varies from a minimum value of $2.0 \times 10^{-3}$% to a maximum value of $9.4 \times 10^{-2}$% (Table 9). This reveals the fact that the environmental impact of exergy destruction dominates over the environmental impact of component design and construction phases. Therefore, attention should be given to reducing or minimizing the thermodynamic inefficiencies in order to improve the environmental performance of the plant. The relative environmental impact difference ranges from 5.13% to 54.76% for the plant components. Like the relative cost difference, this indicator identifies the potential of the plant components for mitigating the unit environmental impact. Similarly, the unit environmental impact of the component having the higher relative environmental impact difference can be reduced with less effort than a component with a lower relative environmental impact difference. Therefore, there is little chance to improve the environmental performance of the GT, AC, APH, and CC units, whereas the HRSG unit can be exergoenvironmentally improved by reducing or minimizing the exergy destruction rate.

Based on the results in Table 10, the HRSG and APH units have the highest total eco-costs/value ratios among the plant components. The total eco-costs/value ratios of the HRSG and APH units are determined at 3.806 USD eco-cost/USD value and 2.919 USD eco-cost/USD value, respectively. Despite the fact that the CC unit is suggested by exergy, exergoeconomic, and exergoenvironmental analyses as the first improvement priority, exergoeconomic and exergoenvironmental analyses ranks it fourth for improvement among the plant components. Interestingly, the HRSG unit is ranked first for improvement with exergoenvironmental analysis. In addition, the HRSG, GT, and HRSG units are respectively suggested by exergy, exergoeconomic, and exergoenvironmental analyses as the second improvement priority. However, the second improvement priority proposed by exergoenvironmental analysis is the APH unit. These differences can be ascribed to the unique conceptual content of exergy cost theory in identifying the real cost sources at the component-level. In general, conventional exergy analysis only deals with quantifying the irreversibility of a given energy system from a local perspective. The obtained irreversibility using exergetic analysis is then directly used in exergoeconomic and exergoenvironmental calculations in order to rank the units based on their improvement potential. Although the obtained insights are useful, they have proven to be inadequate and Lozano and Valero (Lozano and Valero, 1993) comprehensively explained the shortcomings of such local analyses. Exergy cost theory can address these issues by globalizing and quantifying the external resources required to obtain one unit of a given exergy flow. Furthermore, the eco-costs/value ratio approach conceptually

![Sankey diagram for the exergoeconomic analysis of the gas turbine-based cogeneration.](image-url)
consolidates both economic and environmental constraints in a single framework, rationalizing the improvement priority proposed by exergoeconoenviromental method.

The exergoeconoenviromental factor is used to compare the effect of exergy destruction eco-costs/value ratio and component-related eco-costs/value ratio on the total eco-costs/value ratio. A smaller value of the exergoeconoenviromental factor indicates that exergy destruction eco-costs/value ratio of the corresponding component is higher than its design and construction eco-costs/value ratio. However, a larger value of the exergoeconoenviromental factor implies that the design and construction eco-costs/value ratio of the component is higher than the exergy destruction eco-costs/value ratio. The minimum exergoeconoenviromental factor is found to be 0.007% for the AC unit, while its maximum value is determined at 4.948% for the APH unit (Table 10). The exergoeconoenviromental factor is close to zero for all components since the eco-costs/value ratio of exergy destruction is substantially higher than that of the design and construction phases. Accordingly, minimizing the exergy destruction can be used as a practical and useful approach for improving the econoenviromental performance of the plant. The relative eco-costs/value ratio differences of the plant units can be depicted similarly to the relative cost and environmental impact differences, as previously explained. The negative sign of some relative eco-costs/value ratio differences indicates that the eco-costs/value ratio of fuel stream is larger than that of product stream. Overall, the GT and HRSG units have a significant chance to improve the process exergoeconoenviromentally through minimizing the thermodynamic irreversibilities, while the AC and APH units do not have a significant opportunity to improve the process econoenviromentally.

Generally, the methodology proposed herein appears to be a promising tool in the analysis of energy conversion systems at the component-level approach from thermodynamic, economic, and environmental perspectives simultaneously. Future work appears merited towards exploring a way for splitting the eco-costs/value ratio into endogenous/exogenous and avoidable/unavoidable parts in order to improve the quality of the conclusions achieved from exergoeconoenviromental analysis. Such an advanced analysis would be able not only to elucidate the interactions among components of a given energy system but also to discover the real potential for improving the plant components. Note that the methodology used throughout this study for identifying and quantifying the eco-cost values suffers from arbitrariness, inaccuracies, and uncertainties like the other available environmental impact assessment methodologies (Blanco-Marigorta et al., 2014; Meyer et al., 2009; Morosuk and Tsatsaronis, 2012). Accordingly, sensitivity analysis can be used to tackle these problems. Nonetheless, the accuracy and reliability of the exergoeconoenviromental analysis must be improved by evolving the eco-cost determination methodologies. It is pointed out that advances in the
computing the eco-cost values can be easily embedded in the exergoeconoenvironmental analysis. Finally, the proposed methodology can be extended and improved through substituting the eco-costs value ratio by a more inclusive consolidated economic-environmental indicator.

5. Conclusions

An exergoeconoenvironmental analysis methodology is proposed for scrutinizing energy conversion systems from thermodynamic, economic, and environmental point of views concurrently. In this approach, eco-costs/value ratio concept is integrated with exergy cost theory. The integration is similar to the methodology used in exergoeconomic and exergoenvironmental analyses, but eco-costs/value ratios are assigned to unit exergetic costs of exergy streams using the specific exergy costing approach. A well-known and typical gas turbine-based cogeneration system is considered as an example to demonstrate the application of the proposed exergoeconoenvironmental analysis. The results of the developed approach are compared with those of conventional exergy, exergoeconomic, and exergoenvironmental analyses. From the analyses carried out herein, the following main conclusions are drawn:

1) The heat-recovery steam generator has the highest eco-costs/value ratio (3.806 USD eco-cost/USD value), while the lowest eco-costs/value ratio (0.007 USD eco-cost/USD value) is found for the air compressor.

2) According to exergoeconoenvironmental analysis, improvement actions should focus firstly on the heat recovery steam generator and secondly on the air preheater.

3) The exergoeconoenvironmental factor is found to be in the range of 0.007%–4.948%, indicating the fact that eco-costs/value ratio associated with exergy destruction is higher than component-related eco-costs/value ratio.

4) The exergy destruction rate of the plant components should be minimized in order to improve their economoenvironmental performance.

5) The improvement priority proposed by exergoeconoenvironmental approach is different from those suggested by conventional exergy, exergoeconomic, and exergoenvironmental analyses.

Generally, the method proposed herein appears to lead to more informative insights compared with available exergy-based methods for assessing the efficiency, productivity, and sustainability of complex energy conversion systems. This method can support process development in accordance with improved thermodynamic, economic and environmental performance simultaneously. In spite of the fact that the eco-costs determination methodology has some drawbacks, the outcomes of
exergoeconoenvironmental analysis is insightful. Further development of exergoeconoenvironmental analysis through advanced formulations may enable enhanced conclusions for improving the economic and environmental effectiveness of energy conversion systems.

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References


