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Advanced low exergoeconomic (ALEXERGO) assessment of a building along with its heating system at various stages

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ABSTRACT

The present study deals with evaluating the performance of a building heating system along with its main components using advanced low exergoeconomic analysis method. This method combines advanced exergoeconomic with low exergy (LowEx) and is shortly called ALEXERGO. A building heating system is investigated from the energy production to the building envelope stage by stage through the ALEXERGO for the first time by the authors. Based on the results, the generation and distribution stages are found to have bigger exogenous exergy destruction cost rates, meaning that the components in these stages have strong interconnections. The emission (heating) stage has, however, a bigger endogenous exergy destruction cost rate. The generation and emission stages have low improvement potentials while the distribution stage has a big improvement potential. A sensitivity analysis is also made based on the environmental temperature for exergy destruction rates and efficiencies.

1. Introduction

Increasing the energy efficiency in all sectors has been one of the important issues due to the growing concern of environmental problems. In this regard, efficient energy supply for buildings, building complexes and districts has been considered one of main focusing areas based on exergetic principles to coordinate and optimize demand and supply aspects in cities [1]. The Low exergy (LowEx) approach is the concept for the work of ECBCS Annex 49 on energy use and supply structures in the built environment [2]. It has been successfully utilized for analyzing and assessing buildings at various states, such as primary energy production, energy storage, heating/cooling system, building envelope [3].

Exergoeconomic analysis is a combination of exergy and economic analysis methods. It provides the system designer with the information, which is not obtained from conventional exergy and economic assessments. Exergoeconomic analysis method includes cost balances and means for costing exergy transfers and several exergoeconomic variables used in the optimization of the design of thermal systems.

Exergoeconomic is based on the exergy costing principle. A system and its components are investigated for their entire lifetime. All related costs are considered. These are depreciation, return on debt and equity, taxes and insurance, fuel costs and operating and maintenance expenses. The real cost sources in a system include capital investment for each component, operating and maintenance expenses, cost of exergy destruction and cost of exergy loss from the overall system [4].

There are various types of exergoeconomic analysis approaches and methods in the literature. In this context, Rosen and Dincer [5] used several examples to explain general concept of energy, cost, exergy and mass (EXCEM) analysis. In that study, they applied the EXCEM analysis to three components, which were a pump, a steam turbine and a coal fired electricity generator. To calculate cost rates, investment cost and depreciation factor were used. Exergy loss rates of the boiler and the generator turbine were found to be 48.5 MW and 10.2 MW, respectively. Hürdoğan et al. [6] constructed and tested a desiccant cooling system. The EXCEM analysis was applied to the system. Thermodynamic losses, capital costs and their relations were investigated. Electric heater unit, expansion valve, pump, fresh air fan and condenser fan were determined as inefficient unlike other components of the system. Improvement

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potential rates and ratios of thermodynamic loss rate over capital cost varied between 23.72–26.78 kW and 1.14–1.19 MW/US$. Yucer and Hepbasli [7] examined a building heating system by using exergetic and exergoeconomic analysis methods. They combined the LowEx with the exergoeconomic method to investigate the system performance. The stages in the building heating system and the components in these stages were analyzed. The EXCEM analysis was applied to the building heating system. The ratio of thermodynamic loss rate over cost for the generation stage and the steam boiler were calculated as 4.52 W/US$ and 19.77 W/US$, respectively. In another study, the specific exergy costing (SPECO) method was applied to a building along with LowEx method [8]. The exergetic results of the building heating system stages and their cost figures were combined. The exergetic cost coefficients of the generation and emission stages were reported to be 174.67 $/GJ and 256.89 $/GJ, respectively.

In the advanced exergy analysis, the exergy destruction term is divided into certain parts. These are endogenous, exogenous, avoidable and unavoidable. Avoidable/unavoidable exergy destruction concept was presented by Tsatsaronis and Park [9]. Endogenous/exogenous exergy destruction concept was described by Kelly et al. [10]. Morosuk et al. [11] evaluated a LNG regasification and electricity generation system with advanced exergoeconomic and exergoenvironmental methods. They suggested that the focus should be on compressor III and expander II to improve cost effectiveness. Açıkkalp et al. [12] analyzed a trigeneration system by applying the advanced exergoeconomic analysis. The important parameters of the system were exergy efficiency, total exergy destruction, total exergoeconomic factor of the system and electricity generating cost. These were calculated as 0.354, 16.695 MW, 0.069 and 56.249 $/GJ, respectively. The exergy destruction and investment cost values were obtained in four parts (i.e., endogenous, exogenous, avoidable and unavoidable). The results found according to the exogenous part were greater than those of the endogenous part. The improvement potential for the investment flow rate was considered as weak because 88% of them were unavoidable. Açıkkalp et al. [13] also performed advanced exergy analysis of an electricity generation facility. The exergetic efficiency of the system and total exergy destruction rate were calculated to be 0.402 and 78.242 MW, respectively. According to the results of the advanced exergetic and exergoeconomic analyses, the combustion chamber, the high pressure steam turbine and the condenser were the components with the highest potential for improving the system. Those components had the highest exergy destruction cost rates. Keçebaş and Hepbasli [14] compared conventional and advanced exergoeconomic analyses to find potential for energy savings of a geothermal district heating system. The SPECO method was utilized. The conventional and advanced exergoeconomic factors were obtained to be 5.53% and 9.49%. The largest exergy destruction and endogenous exergy destruction cost rates were calculated to be 63.67 $/h and 41.83 $/h. Tan and Keçebaş [15] analyzed a geothermal heating system using advanced exergy and exergoeconomic methods. They determined the improvement potential and cost saving potential of the system were 2.98% and 14.05%, respectively. Keçebaş et al. [16] compared two geothermal district heating system using advanced exergoeconomic method. They concluded that the Sarayköy plant could be operated more economic than the Afyon plant. Khoshgoftar Manesh et al. [17] evaluated a cogeneration system with advanced exergoeconomic and exergoenvironmental methods. In addition to these analyses, malfunction and dysfunction analyses may be applied to various energy systems by considering the thermoeconomic analysis [18,19].

The main objective of this contribution is to apply advanced exergoeconomic analysis to a heating system, which was investigated stage by stage through the LowEx method. In this paper, both the conventional and advanced exergoeconomic analyses are presented in a detailed manner. There are several studies investigating building heating systems by using exergoeconomic analysis. To the best of the authors' knowledge, this is the first attempt that the advanced exergoeconomic analysis and LowEx methods are combined to examine a building heating system.

2. Advanced exergoeconomic analysis

Before making an advanced exergoeconomic analysis, a conventional exergoeconomic analysis has to be done, of which equations are indicated in Table 1.

Endogenous and exogenous parts are described to determine the reasons for the irrevesibilities. The endogenous part presents irreversibilities resulted from the component itself while the exogenous part gives irreversibilities based on other components. The endogenous exergy destruction cost rate, the exogenous exergy destruction rate, the endogenous investment cost rate and the exogenous investment cost rate are calculated as follows, respectively [20]:

$$\dot{C}_{D,k}^{\mathrm{EN}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{EN}} \tag{1}$$

$$\dot{C}_{D,k}^{\mathrm{EX}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{EX}} \tag{2}$$

$$\dot{Z}_{k}^{\mathrm{EN}} = \dot{E}_{k}^{\mathrm{EN}}\left(\frac{\dot{Z}}{\dot{E}_P}\right) \tag{3}$$

$$\dot{Z}_{k}^{\mathrm{EX}} = \dot{Z}_k - \dot{Z}_{k}^{\mathrm{EN}} \tag{4}$$

where $\dot{E}_P$ is the product exergy and $\dot{Z}$ is the investment cost of the component. For describing the improvement potential of the components, avoidable and unavoidable parts are used. The unavoidable part represents technological and economical limits of the component while the avoidable part indicates improvable potential of the considered component. The rates for the avoidable exergy destruction cost, the unavoidable exergy destruction cost, the avoidable investment cost and the unavoidable investment are calculated from [21]:

$$\dot{C}_{D,k}^{\mathrm{AV}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{AV}} \tag{5}$$

$$\dot{C}_{D,k}^{\mathrm{UN}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{UN}} \tag{6}$$

$$\dot{Z}_{k}^{\mathrm{AV}} = \dot{Z}_k - \dot{Z}_{k}^{\mathrm{UN}} \tag{7}$$

$$\dot{Z}_{k}^{\mathrm{UN}} = \dot{E}_{P,k}\left(\frac{\dot{Z}_k}{\dot{E}_{P,k}}\right)^{\mathrm{UN}} \tag{8}$$

The avoidable and unavoidable exergy destruction cost rates are divided into the endogenous and exogenous parts, which are defined here as follows [20]:

$$\dot{C}_{D,k}^{\mathrm{UN,EN}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{UN,EN}} \tag{9}$$

$$\dot{C}_{D,k}^{\mathrm{AV,EN}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{AV,EN}} \tag{10}$$

$$\dot{C}_{D,k}^{\mathrm{UN,EX}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{UN,EX}} \tag{11}$$

$$\dot{C}_{D,k}^{\mathrm{AV,EX}} = c_{F,k}\dot{E}_{D,k}^{\mathrm{AV,EX}} \tag{12}$$

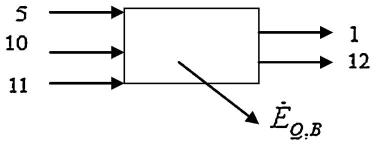
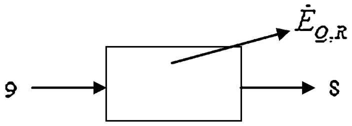
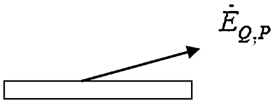
The avoidable and unavoidable costs are divided into the endogenous and exogenous parts, as defined below [21]:

$$\dot{Z}_{k}^{\mathrm{UN,EN}} = \dot{E}_{P,k}^{\mathrm{EN}}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{\mathrm{UN}} \tag{13}$$

$$\dot{Z}_{k}^{\mathrm{UN,EX}} = \dot{Z}_{k}^{\mathrm{UN}} - \dot{Z}_{k}^{\mathrm{UN,EN}} \tag{14}$$

$$\dot{Z}_{k}^{\mathrm{AV,EN}} = \dot{Z}_{k}^{\mathrm{EN}} - \dot{Z}_{k}^{\mathrm{UN,EN}} \tag{15}$$

Table 1
Exergy destruction cost rates for the components.

Component	Illustration	Energy destruction cost rates
B		$\dot{C}_F = \dot{C}_{10}$ $\dot{C}_P = \left(\dot{C}_{12} - \dot{C}_{11}\right) + \left(\dot{C}_5 - \dot{C}_1\right) + \dot{C}_{Q,B}$ $\dot{C}_F + \dot{Z}_B = \dot{C}_P$
HE		$\dot{C}_F = \left(\dot{C}_1 - \dot{C}_2\right)$ $\dot{C}_P = \left(\dot{C}_9 - \dot{C}_8\right)$ $\dot{C}_F + \dot{Z}_{HE} = \dot{C}_P$
WH		$\dot{C}_F = \left(\dot{C}_4 - \dot{C}_5\right)$ $\dot{C}_P = \left(\dot{C}_7 - \dot{C}_6\right)$ $\dot{C}_F + \dot{Z}_{WH} = \dot{C}_P$
R		$\dot{C}_F = \left(\dot{C}_9 - \dot{C}_8\right)$ $\dot{C}_P = \left(c_R \dot{E}_{Q,R}\right)$ $\dot{C}_F + \dot{Z}_R = \dot{C}_P$
P		$\dot{C}_D = \left(c_P \dot{E}_{Q,P}\right)$

$$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX} \tag{16}$$

The exogenous parts of the exergy and the investment costs can be divided into the mexogenous parts. The mexogenous parts of the investment and the exergy costs may be calculated from the following relations [21]:

$$\dot{Z}_{D,k}^{MEX} = \dot{Z}_{D,k}^{EX} - \sum_{\substack{r=1\\ r=k}}^{n} \dot{Z}_{D,k}^{EX,r} \tag{17}$$

$$\dot{C}_{D,k}^{MEX} = \dot{C}_{D,k}^{EX} - \sum_{\substack{r=1\\ r=k}}^{n} \dot{C}_{D,k}^{EX,r} \tag{18}$$

3. System description

A schematic of the heating system with main subsystems is indicated in Fig. 1 where a steam boiler is utilized to heat the building, of which main characteristics are given in Ref. [7]. Fuel-oil is used as a fuel. The energy carrier is circulated by pumps via the distribution system. The generation stage includes a boiler, a distribution stage has a heat exchanger, a water heater and pipes, and the emission stage consists of radiators. A steam boiler (B) is used while the steam gives up its energy to the water in the heat exchanger (HE) where the heat transfer takes place. Energy to the heating system via the distribution system is carried by pipes (P). There are heat exchangers before the water heaters (WH) and heating zones. The emission (heating) system consists of radiators (R), which supply the required heat, to the room air, and the remaining energy is conducted to the building envelope, as seen in Fig. 2. The indoor and outdoor design temperatures for the city of Izmir, Turkey are 20 °C and 0 °C, respectively.

4. Sensitivity analysis

In this section, a sensitivity analysis is conducted based on the environmental temperature for exergy destruction rates and efficiencies. The reason for this is that exergy destruction rates and accordingly exergoeconomic parameters are affected by the environmental temperature importantly. The sensitivity analysis is made using the relation given below [22,23]:

$$\sigma = \frac{(T_o + \Delta T_o)S_{gen} - (T_o)S_{gen}}{(T_o)S_{gen}} = \frac{\Delta T_o}{T_o} \tag{19}$$

where T_o is the environment temperature and S_{gen} is the entropy generation. The results according to $\Delta T_o/T_o$ can be seen in Figs. 3 and 4. The sensitivity of the exergy destruction of the components is shown in Fig. 3. According to this, the water heater is affected mostly from $\Delta T_o/T_o$ while the pipe is affected secondly. The boiler, the water heater and the heat exchanger sensitivity values are between 0 and 0.2. Changes in the sensitivity of exergy efficiencies with $\Delta T_o/T_o$ are indicated in Fig. 4. The sensitivity of the exergy efficiencies of the boiler, the heat exchanger and the radiator varied in a large scale, while the pipes and the water heater are not affected relatively to other components. The effects of the environment temperatures on the exergy destruction and exergy efficiencies are also investigated, as indicated in Figs. 5 and 6. It is clear from these figures that the exergy destruction rates of the water heater and the boiler are affected mostly by the environmental temperature. When investigating Fig. 6, it is understood that the variation of the exergy efficiency of the water heater is the biggest.

5. Results and discussion

This paper presents an advanced exergoeconomic analysis of a building heating system along with the LowEx approach. Before performing the advanced exergoeconomic evaluation, the conventional exergy analysis was done for the system. In Table 2, the exergoeconomic results of the considered system are seen. The

Table 2
Exergoeconomic figures of the system stages.

Stages	$c_{F,k}$ ($/GJ)	$c_{P,k}$ ($/GJ)	$\dot{Z}_k$ ($/h)
Generation	26.16	91.01	0.595
Distribution	91.01	1264.75	0.339
Emission	1264.75	2539.84	0.310

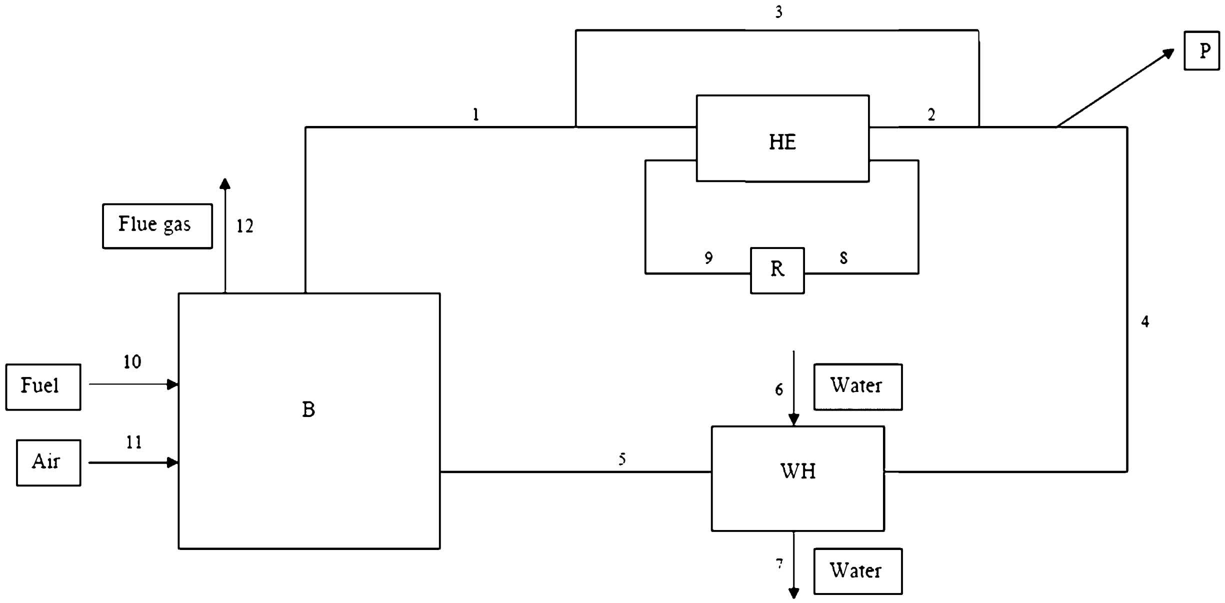


Fig. 1. The heating system investigated.

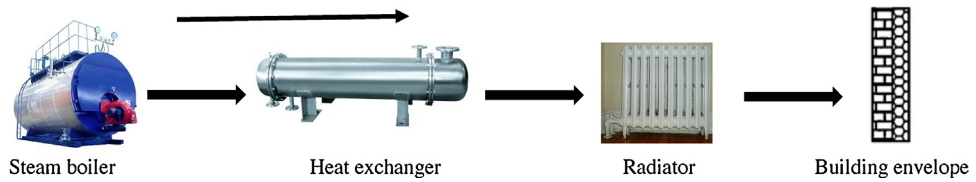


Fig. 2. Exergy flows in the heating system.

fuel exergetic costs are 26.15 \$/GJ, 91.01 \$/GJ, and 1264.75 \$/GJ for the generation, distribution and emission stages, respectively. Similarly, the product exergetic costs are listed to be 91.01 \$/GJ for the generation stage, 1264.75 \$/GJ for the distribution stage and 2539.84 \$/GJ for the emission stage. Finally, the investment cost rate of the generation, distribution and emission stages are 0.595 \$/h, 0.339 \$/h and 0.310 \$/h, respectively.

Endogenous terms present cost irreversibilities or investment rates based on components itself while exogenous terms indicate cost irreversibilities or investment rates of other component on the component's itself. Effects of the any component on the *k* component are described with mexogenous exergy destruction. Unavoidable parts give limits that cannot be improved in the near future. In contrast to this, avoidable parts exhibit improvable rates

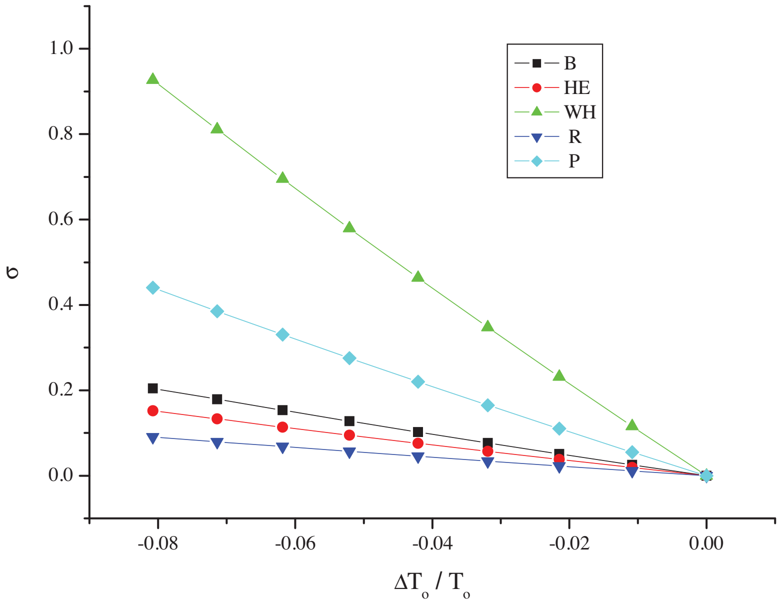


Fig. 3. Results of the sensitivity analysis of exergy destruction rates.

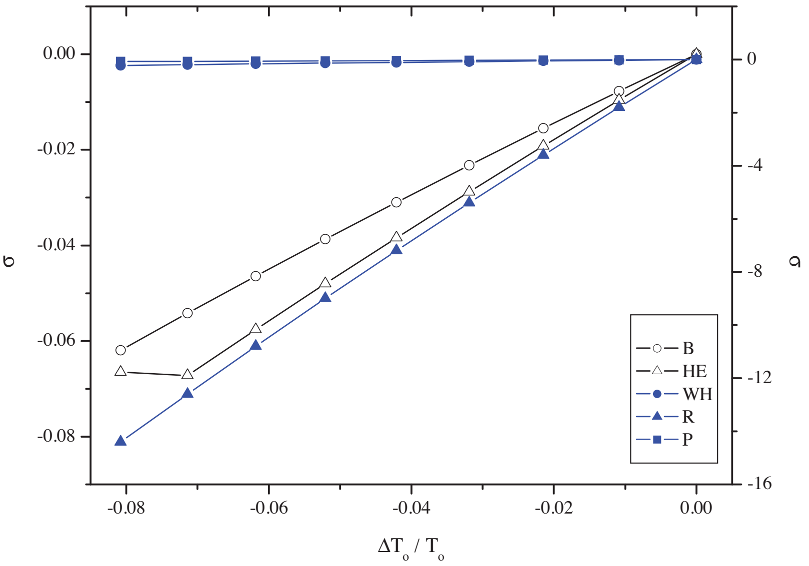


Fig. 4. Results of the sensitivity analysis of exergy efficiencies.

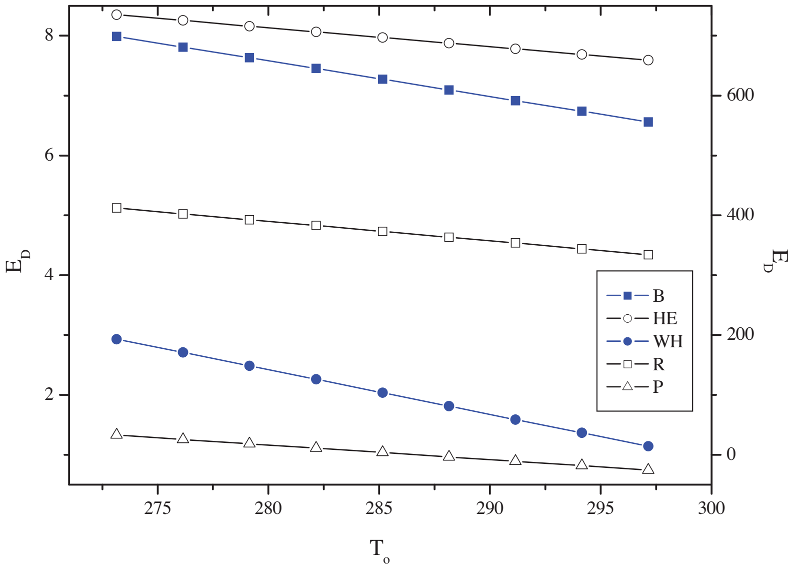


Fig. 5. Effects of the environment temperature on exergy destruction rates.

of the exergy destruction cost rates or investment cost rates. For example; using this information more convenient component, like heat exchanger, can be designed or selected. In this paper, it is assumed that radiators and pipes have no improvable investment cost neither improvable exergy destruction cost rates because of their technological limits. A problem in the analysis is that any theoretical conditions cannot be defined for chemical reacting systems, such as combustion chamber, boiler, etc. However, this problem can be solved with assumptions listed in the following [20,24]:

- The thermodynamic properties of the combustion gas and its composition remain the same as in the real operating conditions.
- The pressure drop in the combustion chamber is negligible.
- State of flue gases at the exit of the boiler should be the result of the chemical reaction in the boiler.
- The excess air at theoretical conditions is equal to the excess air in the real process (or ratio of air mass to fuel mass for real cycle) $\left(\dot{m}_{\text{air}}/\dot{m}_{\text{fuel}} = 14.40\right)$. Thus, compositions of the combustion gasses remain constant.

Table 3
Assumptions made for calculating advanced exergy values.

Components	Real conditions	Theoretical conditions	Unavoidable conditions
B	$\Delta P = 20$ kPa, $\lambda = 1.2$	$\Delta P = 0$ kPa, $\lambda = 1.2$	$\Delta P = 10$ kPa, $\lambda = 1.1$
HE	$\Delta P = 10$ kPa, $\Delta T = 28$ K	$\Delta P = 0$ kPa, $\Delta T = 0$ K	$\Delta P = 5$ kPa, $\Delta T = 18$ K
WH	$\Delta P = 9$ kPa, $\Delta T = 39$ K	$\Delta P = 0$ kPa, $\Delta T = 0$ K	$\Delta P = 5$ kPa, $\Delta T = 33$ K

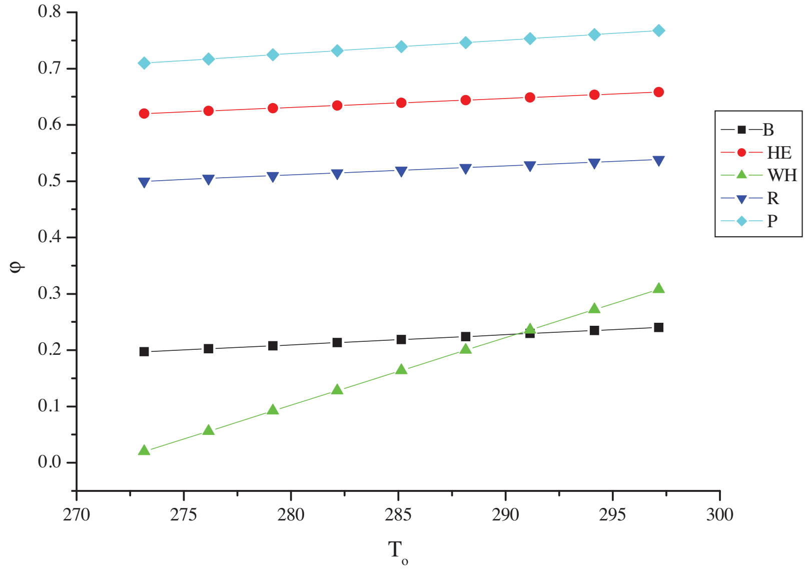


Fig. 6. Effects of the environment temperature on exergy efficiencies.

Table 4
Assumptions made for calculating advanced investment cost values [20].

Components	Unavoidable investment costs
B	90%
HE*	$\Delta P = 10$ kPa, $\Delta T = 60$ K
WH*	$\Delta P = 10$ kPa, $\Delta T = 80$ K

* Unavoidable costs of the heat exchanger were estimated for the above conditions.

- In theoretical conditions, the system is only realized through the exergy balance. In our cases.

$$\dot{E}_{10}^{T} = \left(\dot{E}_{12}^{T} - \dot{E}_{11}^{T}\right) + \left(\dot{E}_{5}^{T} - \dot{E}_{1}^{T}\right) + \dot{E}_{Q,B} \tag{20}$$

More detailed information may be obtained from Refs. [20,24].

Assumptions used in advanced exergoeconomic analysis are presented in Tables 3 and 4 while the results of the advanced exergy destruction cost rates are given in Table 5. As seen from the figure, the endogenous exergy destruction cost rates of the heat exchanger, the radiator and pipes are bigger than the corresponding exogenous parts. However, vice versa is true for the boiler and the water heater. The bigger endogenous exergy destruction cost rate means that the costs of the irreversibilities in the heat exchanger, the radiator, and the boiler are based on the components themselves. In contrast, the exergy destruction costs are mostly resulted from other components. The boiler has the maximum endogenous and exogenous exergy destruction cost rates $\left(\dot{C}_{D,k}^{EN} = 20.876\,\$/\text{h},\quad \dot{C}_{D,k}^{EX} = 45.047\,\$/\text{h}\right)$. In addition, the negative exogenous values indicate that the exergy destruction cost of the component can be decreased by increasing the exergy destruction values of other components. The cost rates for the unavoidable exergy destruction are bigger than those of the avoidable one, except for the water heater. Hence, the improvement potential is low for the system. Although the water heater has a big improvement potential $\left(\dot{C}_{D,k}^{AV} = 3.576\,\$/\text{h}\right)$, this potential is associated with other components. Because its avoidable exogenous destruction cost rates are bigger than its corresponding avoidable endogenous exergy destruction cost rates. The avoidable endogenous exergy destruction cost rate of the heat exchanger has negative value $\left(\dot{C}_{D,k}^{AV,EN} = -0.344\,\$/\text{h}\right)$. The reason for this can be explained with the high mass flow rates while calculating the endogenous exergy destruction rate at this component. As far as the mexogenous exergy destruction cost rate is concerned (Table 7), the boiler is mostly affected by the heat exchanger However, for decreasing the exergy destruction cost rate of the boiler, one should increase the exergy destruction cost rate of the heat exchanger. The water

Table 5
Advanced exergy destruction cost rates of the building heating system.

Component	$\dot{C}_{D,k}$ (\$/h)	$\dot{C}_{D}^{EN}$ (\$/h)	$\dot{C}_{D}^{EX}$ (\$/h)	$\dot{C}_{D,k}^{AV}$ (\$/h)	$\dot{C}_{D,k}^{UN}$ (\$/h)	$\dot{C}_{D,k}^{AV,EN}$ (\$/h)	$\dot{C}_{D,k}^{AV,EX}$ (\$/h)	$\dot{C}_{D,k}^{UN,EN}$ (\$/h)	$\dot{C}_{D,k}^{UN,EX}$ (\$/h)
B	65.923	20.876	45.047	4.552	61.371	8.031	−3.479	12.845	48.526
HE	0.101	0.090	0.011	0.033	0.068	−0.344	0.377	0.445	−0.377
WH	3.682	0.222	3.460	3.576	0.106	0.211	3.365	0.011	0.095
R	0.311	0.311	0	0	0.311	0	0	0.311	0
P	0.005	0.005	0	0	0.005	0	0	0.005	0

Table 6
Advanced investment costs rates of the building heating system.

Component	$\dot{Z}$ (\$/h)	$\dot{Z}^{EN}$ (\$/h)	$\dot{Z}^{EX}$ (\$/h)	$\dot{Z}^{AV}$ (\$/h)	$\dot{Z}^{UN}$ (\$/h)	$\dot{Z}^{AV,EN}$ (\$/h)	$\dot{Z}^{AV,EX}$ (\$/h)	$\dot{Z}^{UN,EN}$ (\$/h)	$\dot{Z}^{UN,EX}$ (\$/h)
B	0.595	0.125	0.470	0.059	0.536	0.013	0.046	0.112	0.424
HE	0.039	0.039	0	0.008	0.031	0.008	0	0.031	0
WH	0.139	0.012	0.127	0.028	0.111	0.003	0.025	0.009	0.102
R	0.310	0.310	0	0	0.310	0	0	0.310	0
P	0.161	0.161	0	0	0.161	0	0	0.161	0

Table 7
Mexogenous exergy destruction cost rates of the building heating system.

Exogenous exergy destruction rate of each component ($/h)	Effects of other components on the exogenous exergy destruction rate ($/h)
B 45.047	HE −20.455 WH 7.147 MX 58.355
WH 3.460	B 0.066 HE 0.102 MX 3.292
HE 0.011	B 0.032 WH 0.010 MX −0.031

Table 8
Mexogenous investment cost rates of the building heating system.

Exogenous investment cost rates of each component ($/h)	Effects of other components on the investment cost rate ($/h)
B 0.470	HE 0.132 WH 0.211 MX 0.127
WH 0.127	B 0.127 HE 0.127 MX −0.127

heater is affected by the heat exchanger mostly. To decrease the heat exchanger's exergy destruction cots rate, one should increase the system's exergy destruction cost rate because of the negative mexogenous exergy destruction cost rate values. A similar evaluation can be made for the investment cost rates. In Table 6, the result of the investment cost rates is indicated. The endogenous investment cost rates are bigger than its corresponding exogenous cost rates for the heat exchanger, radiator and pipes. The boiler and water heater have bigger exogenous cost rates. The maximum endogenous and exogenous investment cost rates are due to the boiler $\left(\dot{Z}^{\mathrm{EN}} = 0.125\,\$/\mathrm{h},\quad \dot{Z}^{\mathrm{EX}} = 0.470\,\$/\mathrm{h}\right)$. The improvement potential of the system investment cost rate is low because of high unavoidable exergy destruction cost rates of the components. The maximum avoidable and unavoidable improvement potential is due to the boiler $\left(\dot{Z}^{\mathrm{AV}} = 0.059\,\$/\mathrm{h},\quad \dot{Z}^{\mathrm{UN}} = 0.536\,\$/\mathrm{h}\right)$. The improvement potentials of the boiler and water heater are mostly associated with other components because of their bigger avoidable exogenous investment cost rates. Investigating the mexogenous exergy investment rates (Table 8) indicates that the boiler is affected by the water heater mostly. The mexogenous investment cost rate is negative and indicates why the investment cost of the system should be increased to decrease the investment cost of the water heater, as indicated in Table 8.

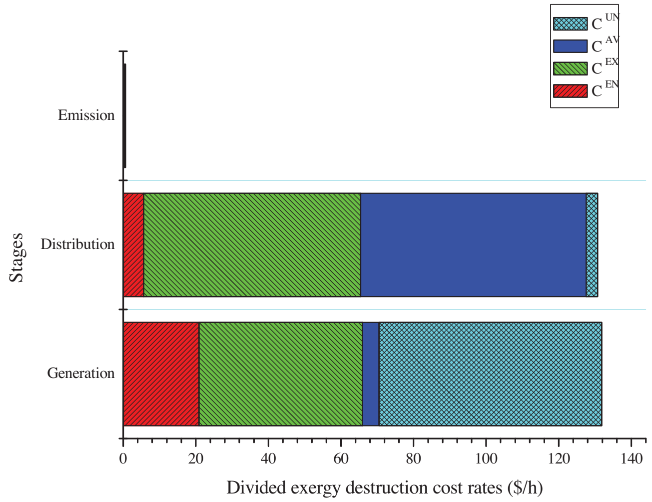


Fig. 7. Divided exergy destruction costs for the system stages.

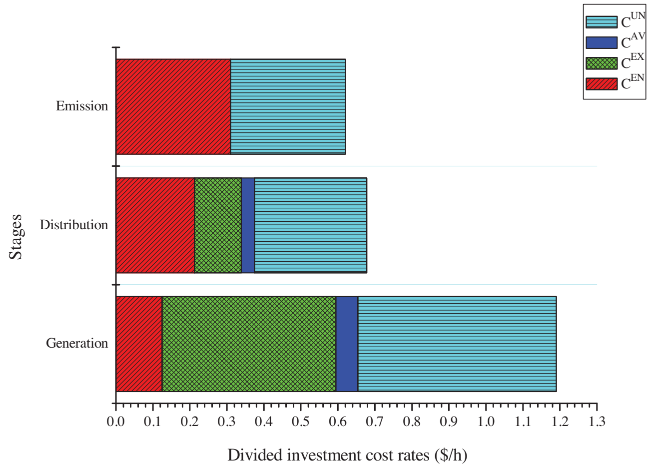


Fig. 8. Divided investment cost rates for the system stages.

The exergy destruction cost rates of the system stages are indicated in Table 9 and Fig. 7. The generation and distribution stages have bigger exogenous exergy destruction cost rates. This means that the components in these stages have strong interconnections. However, the emission (heating) stage has a bigger endogenous exergy destruction cost rate. The exergy destruction cost rate is resulted from this stage. The generation and emission stages have

Table 9
Advanced exergy destruction cost rates for the system stages.

Stages	Endogenous exergy destruction cost rate ($/h)	Exogenous exergy destruction cost rate ($/h)	Avoidable exergy destruction cost rate ($/h)	Unavoidable exergy destruction cost rate ($/h)
Generation	20.876	45.047	4.552	61.371
Distribution	5.652	59.826	62.034	3.230
Emission	0.311	0	0	0.311

Table 10
Advanced investment cost rates for the system stages.

Stages	Endogenous investment cost rate ($/h)	Exogenous investment cost rate ($/h)	Avoidable investment cost rate ($/h)	Unavoidable investment cost rate ($/h)
Generation	0.125	0.470	0.059	0.536
Distribution	0.212	0.127	0.036	0.303
Emission	0.310	0	0	0.310

low improvement potentials while the distribution stage has a big improvement potential.

In Table 10 and Fig. 8, the advanced investment cost rates are listed and illustrated. The distribution and emission stages have bigger endogenous investment cost rates than their exogenous ones. This indicates that the investment costs in these stages can be reduced by focusing on the components in them. However, the investment cost rates can be reduced by improving other components in this stage. The improvement potentials in all stages are lower because of higher unavoidable investment cost rates.

6. Conclusions

We have considered a building heating system along with its main components at various stages from the heat generation to the building envelope in this study. We have assessed the performance of this system using advanced low exergoeconomic analysis method.

We have listed some concluding remarks we have drawn from the results of the present study as follows:

- The generation and distribution stages' exergy destruction cost rates can be improved by focusing on the components in other stages.
- The distribution stage indicates a big improvement potential for exergy destruction cost rate.
- The generation stage's investment cost can be reduced by improving the components in other stages.
- All the improvement potentials of the investment costs are low.
- One should focus on the heat exchanger for the improvement efforts for exergy destruction cost rate.

It is recommended for a future study that advanced exergoenvironmental analysis be applied to various building heating systems. In addition to that, malfunction and dysfunction analyses may be adapted to advanced exergy based methods.

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