



Exergoeconomic and enviroeconomic analyses of a building heating system using SPECO and Lowex methods



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ABSTRACT

This study deals with exergetic and exergoeconomic analyses of a building heating system, which is examined from the generation component to the envelope of the building. The energy and exergy flows between the components are calculated using the predesign tool for an optimized building design. To the best of the authors' knowledge, the specific exergy costing (SPECO) method is applied to a building along with a low-exergy (also referred to as Lowex) analysis for the first time. By adding the value from the generation to the emission components, the exergetic cost coefficients of the products are determined to be 174.67 \$/GJ and 256.89 \$/GJ, respectively. Exergetic cost effectiveness (ECE) parameter is used to decide about which components will be improved. The first two high values are found to be 0.469 and 0.0057 for the generation and the building envelope, respectively.

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1. Introduction

Exergy analysis is a thermodynamic method, which has been commonly applied since 1950s as a very useful tool. Exergy term was firstly used by Rant in 1956. Exergy can be defined in various ways, as also highlighted and reviewed by Hepbasli elsewhere [1]. According to one definition, it means the maximum work that can be obtained from an energy system. Because a portion of energy turns out to be exergy, it can be called quality of the energy in a system. Exergy enables investigators and engineers the opportunity to assess the performance of energy systems in terms of their quality levels.

Energy systems in buildings are operated under the strong influence of the environment. Their thermodynamic variables are very close to outdoor (ambient) conditions. The energy demand of buildings is important. Likewise the exergy demand is one of the most important variables of exergy analysis in buildings. It indicates the minimum amount of work needed for providing appropriate indoor conditions to buildings. Exergy analysis focuses on the available portion of the energy while conventional analysis takes energetic values into account. Energy analysis contains all the energy forms. In fact, some of them (irreversibilities) cannot be used in the

system. Inefficiencies caused by the irreversibilities within the system being considered are only identifiable with the aid of an exergetic analysis. Exergy based methods reveal the location, the magnitude and the sources of inefficiencies and costs.

In thermal systems, the true cost, at which each of the utilities is generated, assists in determining cost ineffective processes. One can identify technical options that may improve the cost effectiveness of the system. Exergoeconomics, which is a combination of exergy with economics, can be considered as exergy aided cost minimization [2]. In the literature, there are certain methods, which examine both exergy and cost figures of any system. One of the most commonly used methods is the specific exergy costing (the so-called SPECO) analysis. Ameri et al. [3] estimated the exergy destruction and exergy loss of each component in a steam power plant. The exergy efficiencies of the boiler, the turbine, the pump, the heaters, and the condenser in this plant were calculated at different ambient temperatures. The results obtained that energy loss rates mainly occurred in the condenser as 306.9 MW. Only 67.63 MW was lost from the boiler. On the other hand, the irreversibility of the boiler was higher than that of other components. As the operating load increased, the exergy efficiency of the components increased. The plant was designed for the full load. Kanoglu et al. [4] developed exergy flows, cost formation and allocation within a high temperature steam electrolysis (HTSE) system. They used the SPECO methodology while they applied exergetic fuel and product approaches to obtain the cost balance equations. They studied on exergy efficiency, exergy destruction rates, exergy

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loss–exergy destruction ratio, capital investment, operating and maintenance costs and exergoeconomic factor. The capital investment cost, the operating and maintenance costs and the total cost of the system were calculated as 422.2, 2.04 and 424.3 €/kWh, respectively. The cost distribution among the components was also determined. The exergetic costs of the steam were 0.000509, 0.000544 and 0.000574 €/kWh at the outdoor temperatures of 25 °C, 11 °C and –1 °C, respectively. Orhan et al. [5] studied to minimize cost of a copper–chlorine (Cu–Cl) thermochemical cycle for hydrogen production. The SPECO method was used to determine changes in design parameters of the cycle, which could improve the cost effectiveness of overall system. It was found that the cost rate of the exergy destruction took the values between \$1 and \$15 per kg hydrogen. The exergoeconomic factors were calculated between 0.5 and 0.02. Bagdanavicius et al. [6] assessed the community energy supply (CES) systems using energy, exergy and exergoeconomic analyses while they studied four CES systems. An exergoeconomic evaluation was performed using the SPECO approach. Exergy costs of heat and electricity were calculated. The lifetime of the combined heat and power (CHP) system was assumed as 20 years. The interest rate on the capital was used as 10% and the yearly operation duration of the plant was 7000 h. The unit energy price of natural gas was taken to be 0.0205 €/kWh. In the system analysis, the values for the exergy efficiency, the exergy destruction ratio, the relative cost difference and the exergoeconomic factor were determined. Lazzaretto and Tsatsaronis [7] proposed a methodology for defining and calculating exergetic efficiencies and exergy related costs in thermal systems. It was based on the SPECO. Separate forms of exergy and costs associated with these exergy streams were used to define exergetic efficiencies in a detailed manner. It was concluded that the SPECO was a powerful approach to express the validation of the calculated cost values. Kalinci et al. [8] investigated a plasma gasification process. They utilized the SPECO method to calculate exergy related parameters and to obtain cost flows for all streams and components. Exergy destruction values along with their costs were calculated. The exergy destruction ratios and exergoeconomic factors were obtained for all components in the system. The SPECO method was used to improve cost effectiveness according to the exergy rates.

In the first law of thermodynamics, it is stated that energy can never be lost while exergy can be lost. This loss is caused due to the irreversibilities, which can be minimized using low exergy requiring or exergy efficient systems. Exergy loss leads to environmental causes. Environmental effects are associated with emissions. As a result of the combustion of fuels, carbon monoxide (CO), sulfur dioxide (SO₂) and nitrogen oxide (NO_x) based gases. These gases have harmful effects on human's health. For example, the exhaust gases from a car or the flue gas from a boiler. Energy, exergy, environment and sustainable development are strongly related with each other. Environmental issues play an important role in the changing world. The emission value of carbon dioxide (CO₂) is used to decide on the cost figure for the pollution level. In this regard, Caliskan et al. [9] presented a paper dealing with the energy, exergy, environmental, exergoeconomic and sustainability analyses of the Maisotsenko cycle based novel air cooler. They calculated exergy input, output, loss and destruction rates using exergy analysis method. The exergetic coefficient of performance and exergy efficiency values were also obtained. In the environmental analysis, the CO₂ emission of air cooler in a year was found. After obtaining the exergetic and environmental values, sustainability, exergetic cost and environmental cost figures were calculated.

In the open literature, there are various studies using Lowex method to calculate heat losses in exergy values. The authors also utilized both this useful tool and exergoeconomic analysis method (exergy, cost, energy and mass: the so-called EXCEM) [10,11]. In this paper, they applied the SPECO method to the results of the Lowex

Table 1

Characteristics and cost figures of the exterior wall.

Component	Quantity (m ²)	Unit cost	Total cost (\$)
Brick	1082	0.1 \$/361 cm ²	2997.23
Interior plaster	1082	0.44 \$/m ²	480.89
Exterior plaster	1082	0.44 \$/m ²	480.89

predesign tool. For the first time, exergy loss rates of a building heating system were evaluated with the cost figures calculated by the SPECO method for that system. The costs were based on the capital, operation and maintenance cost figures of equipment and the building components in the overall system. In this context, the main objectives of this contribution are to (i) apply exergy analysis to a building heating system, (ii) use the exergy loss findings to perform exergoeconomic analyses, (iii) assess its performance, and (iv) perform the CO₂ emission based enviroeconomic analysis.

2. System description

2.1. Heating system

Exergy loss is one of the most important factors in the exergy concept. The heating system mainly consists of generation, distribution and emission components. In generation component, to meet the requirements for heating and domestic hot water, a steam boiler is deployed. The type of the fuel consumed is fuel oil. The heat exchanger transfers the heat energy of the steam to the hot water in the system where the domestic hot water (DHW) is produced.

The distribution component includes pipes. In this study, the pipes between the heating center and the heating zone are taken into account. The existing pipe type is a screwed pipe.

At the emission stage, there are panel radiators to heat the rooms. Finally, the remaining exergy reaches the building envelope and leaves the building.

2.2. Building characteristics

The heated zone of the examined heating center is a building used as a house of accommodation. There are 49 rooms in this building with three floors. The building has an inside volume of 5850 m³ and a net floor area of 650 m². It is an old building and there is no insulation in the exterior walls. The exterior wall consists of air brick and plaster for exterior and interior surfaces. The thermal transmittance value of the exterior wall is determined to be 0.96 W/m² K. The floor to the ground consists of floor tile plate, cement, concrete, tap cinder and blockage on soil. The thermal transmittance value of the floor to the ground is calculated to be 0.80 W/m² K. The ceiling consists of glass wool, concrete and plaster for interior surface. The thermal transmittance value of the roof is calculated to be 0.43 W/m² K. The heating insulation project of the building according to the Turkish Building Standard, TS 825 [12], the calculated thermal transmittance values are appropriate. The indoor and outdoor air temperatures are 21 °C and 0 °C, respectively.

3. Analyses

3.1. Determination of building envelope materials' costs

In this study, the investigated building has three floors (including basement) with a height of 10 m. Total calculated wall surface area of the building is 1082 m². The components in the exterior wall are air brick, interior and exterior plasters. The characteristics and cost figures for the exterior wall are presented in Table 1.

Table 2
Characteristics and cost figures of the components.

Component	Quantity	Unit cost	Total cost (\$)
3 in. pipe	63 m	7.25 \$/m	3278.61
5 in. pipe	183 m	15.42 \$/m	
Radiator	600 mm × 1200 mm (49 units)	97.42 \$/m	5728.296
Steam boiler	1 unit	13,810.17 \$	13,810.17

Table 3
Relations for the heat loss analysis.

Type of loss	Relations
Transmission heat loss	$\dot{Q}_T = \sum_i (U_i \cdot A_i \cdot F_{xi}) \cdot (T_i - T_0)$
Specific transmission loss	$H_{tr} = \sum_i (U_i \cdot A_i \cdot F_{xi}) / A$
Ventilation heat loss	$\dot{Q}_V = (c_p \cdot \rho \cdot V \cdot n_d \cdot (1 - \eta_V)) \cdot (T_i - T_0)$
Heat demand	$\dot{Q}_T + \dot{Q}_V = \dot{Q}_H$
Specific heat demand	$\frac{\dot{Q}_H''}{A_N}$

The cost figures are taken from Ministry of Environment and Urban Planning's Bill of Quantities.

3.2. Determination of heating system components' costs

The heating system considered consists of the generation, distribution and emission stages. The generation component is a steam boiler. The distribution component has pipes with different sizes. The emission component consists of 49 panel radiators. The characteristics and cost figures of the components in the heating system are presented in Table 2. The cost figures are taken from Ministry of Environment and Urban Planning's Bill of Quantities.

3.3. Determination of energy demand

The characteristics of building and heating components are considered to calculate heat losses of the examined building. An Excel tool developed within the framework of IEA ECBCS Annex 49 [13] is utilized. The heat losses include the transmission heat loss and ventilation heat loss rates. A sum of all losses from the building components are taken to obtain transmission heat losses. The transmission heat loss rates for each of the building components are presented in Fig. 1.

In this paper, solar and internal heat gain rates are neglected. The relations for the heat loss rates are shown in Table 3.

3.4. SPECO analysis

The SPECO method is generally preferred more than other exergoeconomic methods. Total cost of exiting streams in a system that examined according to the cost balance equation is equal to the sum of entering streams' costs, capital cost, operating and maintenance costs. The cost balance equation can be written as follows:

$$\dot{C}_F + \dot{Z} = \dot{C}_P \quad (1)$$

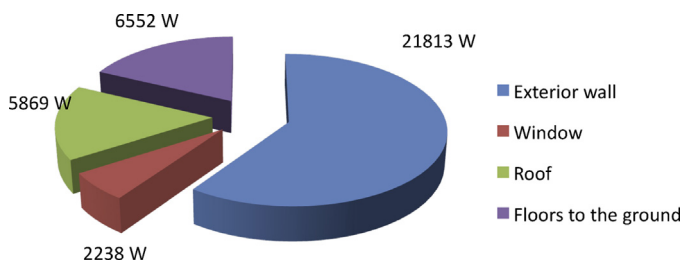


Fig. 1. Transmission loss rates for the building parts.

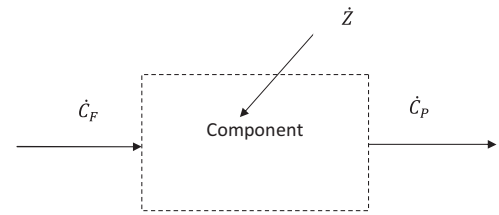


Fig. 2. Cost balance figure of a component.

where \dot{C}_F and \dot{C}_P denote the costs of the entering and exiting streams, respectively. \dot{Z} stands for the capital cost, operating and maintenance costs. This relation is schematically shown in Fig. 2.

The capital cost is the purchase cost of the equipment and may be obtained easily. However, this situation is not the same for operation and maintenance costs. These costs are calculated by applying the following relation:

$$\dot{Z}_k = \frac{\dot{Z}_k \cdot CRF \cdot \varphi}{N \cdot 3600} \quad (2)$$

where k index represents an equipment or a component, Z_k is the capital cost of equipment k and CRF denotes the capital recovery factor, which is calculated by

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

where i represents the interest rate, n is the total operating period of the equipment in years, N denotes annual number of operation hours of the equipment and φ is the maintenance factor.

Thermoeconomy rests on the ration that exergy is the only rational basis for assigning costs to the interactions that system experiences. A cost rate of any figure is calculated by multiplication of exergetic cost coefficient value (C_i) and exergy value ($\dot{E}x_i$) of that figure as follows:

$$C_i = c_i \dot{E}x_i \quad (4)$$

3.5. Exergetic and exergoeconomic analyses of the heating system

3.5.1. Exergetic analysis of the heating system

Steam boiler is equipment which generates steam at the required pressure, temperature and quantity. It is assumed as an open system thermodynamically.

Exergy analysis is performed by balancing the exergy input (fuel) rates and exergy output (product) rates in the control volume. In this study, the exergy of air to burn the fuel is neglected. The exergy rates of flue gas and heat loss from the surface are included in the exergy loss term. The exergy balance can be written as follows:

$$\dot{E}x_f = \dot{E}x_p + \dot{E}x_{loss} \quad (5)$$

which means that the exergy rate entering the control volume ($\dot{E}x_f$) is equal to the exergy rate exiting from the control volume ($\dot{E}x_p$) and the exergy loss rate ($\dot{E}x_{loss}$).

Exergetic efficiency can be calculated from

$$\psi = \frac{\dot{E}x_p}{\dot{E}x_f} \quad (6)$$

Sustainability index (SI) can be determined by [14]

$$\psi = 1 - \frac{1}{SI} \quad (7)$$

Following the same way, the exergy balance equations of the distribution and emission components can be constructed. Their exergetic efficiencies and sustainability indices can be then calculated.

3.5.2. Exergoeconomic analysis of the heating system

The heating system components are analyzed separately and for each component, the cost balance equation (Eq. (1)) is used. To find the exergetic cost values, one should make assumptions for the cost balance equation. In the examined heating system, the generation component is a steam boiler. The exergetic cost coefficient values of water and air at the inlet are taken as zero. The exergetic cost coefficient value of the fuel ($c_{g,f}$) can be calculated because the purchase cost of the fuel oil is known. Then, unknown exergetic cost value ($c_{g,p}$) can be calculated.

$$c_{g,f} \cdot \dot{E}x_{g,f} + \dot{Z}_g = c_{g,p} \cdot \dot{E}x_{g,p} \quad (8)$$

where $c_{g,p}$ represents the product of the steam boiler, exergetic cost coefficient of steam. Likewise exergetic cost coefficient values for the components distribution and emission are calculated using the following relations:

$$c_{d,f} \cdot \dot{E}x_{d,f} + \dot{Z}_d = c_{d,p} \cdot \dot{E}x_{d,p} \quad (9)$$

$$c_{e,f} \cdot \dot{E}x_{e,f} + \dot{Z}_e = c_{e,p} \cdot \dot{E}x_{e,p} \quad (10)$$

The exiting stream of the generation is the entering stream of the distribution. Thus, the calculated exergetic cost coefficient value of the exiting stream can be used as the entering stream for the next component. For example, the exergetic cost coefficient of the outlet stream of the generation is equal to the exergetic cost coefficient of the inlet stream of the distribution.

$$c_{g,p} = c_{d,f} \quad (11)$$

The exergy rates used to calculate these cost figures are the findings obtained from performing the Lowex analysis method.

3.5.3. Enviroeconomic analyses of the heating system

Environmental analysis is of great concern because energy consumption results in climate changes, acid rains and ozone depletion. Main greenhouse gas, CO₂ emission, causes most of the environmental effects. The following formula is utilized [9]:

$$x_{CO_2} = \frac{y_{CO_2} \dot{W}_{con} t_{op}}{10^6} \quad (12)$$

where x_{CO_2} the CO₂ emission is released in a year (tCO₂/year), y_{CO_2} is the CO₂ emission value of firing fuel oil (0.27 kg CO₂/kW h [11]), \dot{W}_{con} is the power equivalent for the amount of fuel oil consumed in a year and t_{op} is the yearly operating hours of the equipment in a year.

Enviroeconomic (environmental) analysis is based on the carbon price and the released carbon quantity. The carbon price forms the motivation to decrease or stop CO₂ emissions to obtain more clean world. International carbon price is assumed as 14.5 \$/tCO₂ [15]. In this study, fuel oil is the source of energy for heating the zones and meeting the domestic hot water requirements. As the steam boiler works, it consumes amount of fuel oil and thus amount of CO₂ is released to the atmosphere. The cost caused by CO₂ emission is calculated by

$$C_{CO_2} = c_{CO_2} \cdot x_{CO_2} \quad (13)$$

where C_{CO_2} denotes enviroeconomic cost based on the CO₂ emission per year, c_{CO_2} is the CO₂ emission price per tCO₂ and x_{CO_2} is the yearly CO₂ emission value. According to the yearly fuel consumption values for heating and domestic hot water, the findings are listed in Table 4.

3.5.4. Exergetic cost effectiveness (ECE) analysis of the heating system

The components in the heating system are investigated according to their exergy figures. Investment, operation and maintenance costs are also studied. The ECE analysis has been recently proposed

Table 4

Annual fuel oil consumptions of heating and DHW systems.

System	Consumption (kg)	CO ₂ emission (kg/year)	Total cost (\$)
Heating	23,628.3	292.7	4.24
DHW	20,000	247.77	3.59

Cost of CO₂ emission: 14.5 \$/tCO₂.

by the authors [11] and focuses on the component, which costs more and causes more exergy loss. From the generation step to the building envelope, the exergy and cost findings are used to calculate the ECE values.

The contribution of a component to the total cost (a) is calculated as follows:

$$a = \frac{\text{cost of a component}}{\text{total cost of the system}} \quad (14)$$

The contribution of a component to the total exergy loss (b) is formulated as

$$b = \frac{\text{exergy loss of a component}}{\text{total exergy loss of the system}} \quad (15)$$

The ECE parameter is obtained by applying the following expression.

$$ECE = a \cdot b \quad (16)$$

4. Results and discussion

4.1. Exergetic results

A predesign tool Annex 49 includes energy and exergy results of the chosen building along with its heating system. The detailed application of the Lowex approach to various systems is given by Hepbasli elsewhere [1]. Here, some part of the Lowex analysis is explained. For example, the source of the generation component is selected. Some design parameters, which are included in the program used to calculate energy and exergy values of the generation component (boiler). For example, as a source of heat production, the “district heat” is chosen from the software program of the Lowex approach. According to the heat production, the source thermal efficiency and max. supply temperature are taken to be 0.89 and is 110 °C, respectively. The results of the Lowex analysis are used in this study. No further calculations are made for energy and exergy values.

According to the project data used in the predesign tool, the transmission and ventilation heat loss rates are found to be 36.47 kW and 16.46 kW, respectively. The specific transmission heat loss rate is found to be 0.71 W/m². The heat demand rate of the building and the specific heat demand rate are calculated to be 52.935 kW and 81.44 W/m², respectively. The energy and exergy load rates are listed in Table 5, while energy and exergy loss rates obtained by applying the predesign tool are shown in Table 6. The energy and exergy flows in the heating system are illustrated in Fig. 3.

Table 5

Energy and exergy rates of the system.

Stages	Energy load rate (kW)	Exergy load rate (kW)
Input	113.93	107.09
After prim. en. trans.	87.64	82.38
After generation	78	17.15
After distribution	55.72	12.61
After emission	52.94	11.93
After room	52.94	3.78
After envelope	52.94	0

Table 6
Energy and exergy loss rates of the system.

Steps	Energy loss rate (kW)	Exergy loss rate (kW)
After prim. en. trans.	26.29	24.71
After generation	9.64	65.23
After distribution	22.27	4.54
After emission	2.79	0.69
After room	0	8.15
After envelope	0	3.78

Table 7
Exergoeconomic figures of the system.

Equipment	Exergoeconomic figures		
Generation	$C_{g,f}$ 26.78 \$/GJ	\dot{Z}_g 0.46 \$/h	$C_{g,p}$ 174.67 \$/GJ
Distribution	$C_{d,f}$ 174.67 \$/GJ	\dot{Z}_d 0.07 \$/h	$C_{d,p}$ 239.11 \$/GJ
Emission	$C_{e,f}$ 239.11 \$/GJ	\dot{Z}_e 0.17 \$/h	$C_{e,p}$ 256.89 \$/GJ

After calculating the predesign tool results, the energy and exergy input rates to the system are approximately 113.925 kW and 107.089 kW, respectively. After each component, the energy and exergy rates decrease until they reach the building envelope. An energy rate of 52.935 kW is transferred to the room. As an exergy rate, it is only 11.925 kW. On the other hand, the maximum exergy loss rate took place at the generation stage in the steam boiler as 89.939 kW.

The equipment that form the components in the heating system are a steam boiler (generation), pipes (distribution) and panel radiators (emission). Exergetic efficiencies of these components are 16%, 73% and 94%, respectively. The exergetic efficiency of the overall system is found to be 3.46%. By comparison, this value remains between the exergy efficiency values of 0.40–25.3%, which were reported by Hepbasli [1].

The sustainability index for the generation in this study is determined to be 1.19. Because the distribution and emission components are more efficient compared to the generation, their sustainability indices are higher. It is calculated to be 3.77 for the distribution and 16.67 for the emission.

4.2. Exergoeconomic results

The SPECO method is applied to the components in the heating system. The exergoeconomic results are presented in Table 7. It can be seen that the maximum exergetic cost coefficient belongs to emission component. Since a certain amount of value is added to

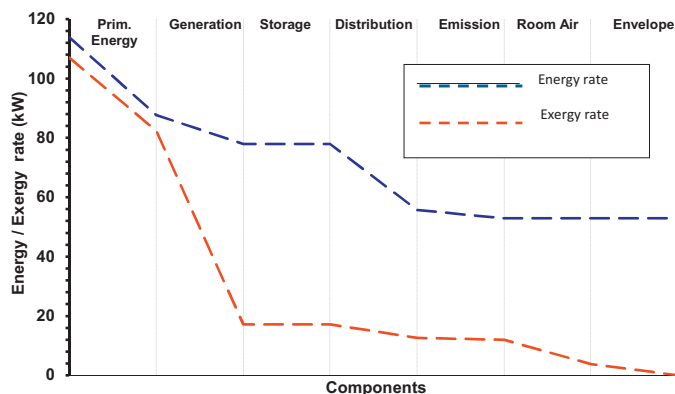


Fig. 3. Energy and exergy rate flows through components.

Table 8
ECE results of the system.

Components	$\dot{E}_{x,loss}$ (kW)	C (\$)	a	b	ECE (a-b)
Generation	89.94	13,810	0.516	0.909	0.469
Distribution	4.54	3278	0.122	0.046	0.0055
Emission	0.69	5728	0.214	0.007	0.0015
Building envelope	3.78	3959	0.148	0.038	0.0057

the energy carrier (steam or water), the cost coefficient increases from the generation step to the emission step.

The capital cost figures of each component are taken from the Ministry of Environment and Urban Planning's Bill of Quantities. In this paper, the cost and exergy loss rates for the outdoor pipes are taken into consideration.

Each component is evaluated by comparing its ECE value with that of other components. According to the "a" index, the generation step has the maximum value with 0.516. The minimum value belongs to the distribution step and is obtained to be 0.122. On the other hand, "b" index of the generation step has the maximum value of 0.909. The lowest "b" index is 0.007 and is calculated for the emission step. These findings show that the generation step needs to be examined firstly. A new and more efficient version of a steam boiler can be chosen to reduce the exergy loss rates. The ECE value for the generation is 0.469. The findings related to the ECE analysis are presented in Table 8.

5. Conclusions

In this study, we applied exergetic and exergoeconomic analyses to a building heating system. Using the predesign tool in Annex 49, we calculated energy and exergy flows from the first stage, primary energy source to the last stage building envelope. We also performed an exergoeconomic analysis on the steps after determining the exergetic results in the Lowex predesign tool defined in Annex 49. Finally, we obtained the environmental costs as an environmental analysis.

We may list some concluding remarks we drawn from the results of the present study as follows:

- Total exergy input rate was determined to be 107.09 kW while the largest exergy loss rate was calculated as 89.9 kW.
- The overall system exergy efficiency was calculated to be 3.46%.
- By examining the exergetic cost coefficients, the maximum value belonged to the emission step as 256.89 \$/GJ. The distribution and generation steps had exergetic cost coefficients of 239.11 \$/GJ and 174.67 \$/GJ, respectively.
- The components with the high ECE values should be chosen to make analysis for improvements. According to the findings, the generation step (0.469) had the maximum ECE value among other ones. The distribution, the emission and the building envelope had ECE values of 0.0055, 0.0015 and 0.0057, respectively.
- In the environmental analysis, the yearly released CO₂ amount for heating and domestic hot water was obtained to be 292.7 kg and 247.77 kg, respectively.
- In this study, we utilized a Lowex approach based on static calculation methods, which may not be very precise compared to dynamic calculation methods. The difference between the uses of energy demand prediction of the static and dynamic calculation methods can be even larger than the savings of the exergetic prediction of the distribution system. Modern building simulation programs, such as TRNSYS and EnergyPlus, could be utilized to illustrate the specific heat flow of envelope parts. In this regard, performing a dynamic exergetic assessment is recommended.

- (g) For a future work, a life cycle impact assessment using various indicators can also be made to understand pollution levels.

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