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# Comparative exergoenvironmental analysis and assessment of various residential heating systems

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ABSTRACT

This paper uses exergoenvironmental analysis to tackle the energetic, exergetic, and environmental performance of three heating systems commonly used in the residential building sector in Turkey: a conventional coal boiler, a condensing natural gas boiler, and a ground source heat pump. This analysis presents a combination of exergy analysis and life cycle assessment (LCA). The obtained results show that the ground source heat pump is an efficient heating system for the given application from a thermodynamic perspective in terms of the coefficient of performance and exergy efficiency with values of 2.5 and 10%, respectively. On the other hand, the LCA results demonstrate that the system-related environmental impact associated with ground source heat pump is the highest among the compared systems. Based on exergoenvironmental analysis the environmental impact per kWh exergy demand for each system is found to be 4.0, 1.69, and 1.93 mPt/kWh, respectively. This demonstrates that using an efficient system from thermodynamic perspective does not offer a significant environmental advantage and Turkey must renounce the use of coal in heating applications as soon as possible in order to get rid of environmental burdens as the first step and should promote the use of natural gas at building level in order to generate heating energy.



## 1. Introduction

The world energy crisis and increasing environmental awareness globally have made many countries reconsider the equipment used in energy conversion, particularly in the building sector for last forty years. As a consequence, the concept of sustainability has entered the engineering world, and it appears to be connected with every aspect of an engineer's profession. In the building sector, building sustainability is a means to provide a safe, healthy, comfortable indoor environment while simultaneously limiting the impact on the Earth's natural resources [1]. In other words, HVAC design engineers' concern must not only be the reduction of the energy use by HVAC systems, but also the mitigation of the related environmental impacts.

In the complex domain of sustainability, a multitude of analytical tools are being used individually or in a hybrid form to grasp a productive situation in its complexity as well as complete comparison between different pathways that fulfill the same function such as exergy analysis and life cycle assessment (LCA). Exergy analysis is a popular analytical tool used to study thermodynamic inefficiencies in systems and is thus relevant in revealing improvement potential [2]. Exergy analysis comes to complete the weakness of energy analysis by taking the quality of the energy into account as well as the quantity. Life cycle assessment aims at compiling and evaluating the environmental impacts of a system from a life cycle perspective. Each analytical tool reflects upon a problem from a specific perspective. Exergy analysis pays attention to inefficiencies within a system from a thermodynamic perspective, while LCA focuses on integrating details and the environmental impacts of a system within a life-cycle perspective. Thus, decision making based on one perspective without considering the other perspectives may lead to an unacceptable result.

For example, in HVAC applications, International Energy Agency (IEA) Annex 37 [3] performed exergy analyses to evaluate the energy performance of heating systems and their components. The results have shown that there is an enormous waste of exergy when high quality energy, such as electricity and fossil fuel, is used in heating applications. Consequently, low quality energy tasks such as space heating can be performed more efficiently and less expensively by other means, such as geothermal energy and solar energy; ground source heat pumps are an excellent way to make use of the low quality heat from the ground to provide for the low quality energy demand of space heating. Based on this reality, many researchers have used exergy analysis to compare conventional heating systems such as boilers and furnaces, which use fossil fuel like coal and natural gas, and modern heating systems such as heat

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**Nomenclature**

| | |
|---|---|
| $\dot{Q}_h$ | heating energy demand rate (W) |
| $K_{tot}$ | total heat loss coefficient of the building (W/°C) |
| $T$ | temperature (°C) |
| $F$ | quality factor or Carnot efficiency |
| $\dot{E}x$ | exergy rate (W) |
| $j$ | $j$th stream |
| $\dot{B}$ | environmental impact per unit of exergy (Pt/J) |
| $b$ | environmental impact rate associated with exergy (Pt/s) |
| $\dot{V}$ | volumetric flow rate ($m^3$/s) |
| $\dot{P}$ | pressure loss rate (kPa) |
| $\Delta T$ | temperature difference (°C) |

*Abbreviations*

| | |
|---|---|
| HVAC | heating ventilation and air conditioning |
| LCA | life cycle assessment |
| COP | coefficient of performance |
| GSHP | ground source heat pump |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | exergetic efficiency |
| $\rho$ | density (kg/$m^3$) |
| $\eta$ | energy efficiency (%) |

*Subscripts*

| | |
|---|---|
| tot | total |
| 0 | outside or reference |
| i | inside |
| q | quality |
| h | heating |
| s | system |
| G | generation |
| dis | distribution |
| em | emission |
| ls | losses |
| mech | mechanical |
| hydro | hydraulically |
| w | water |
| D | destruction |
| F | fuel |
| P | product |

pumps, which extract low-grade unusable heat from the environment (air, ground or water) and convert it into high-grade heat for space heating.

Balta et al. [4] compared a heat pump, a condensing boiler, a conventional boiler and a solar collector as an alternative heating system for a building. The results showed that the heat pump has a higher exergetic sustainability index after the solar collector for the considered application. Yildiz and Gungor [5] compared a liquid natural gas (LNG) fired conventional boiler, an LNG condensing boiler, and an external air to air heat pump as heat generation units for an office heating source. This comparative study showed that an external air to air heat pump has the highest efficiency in terms of energy and exergy. Balta et al. [6] compared seven alternative heating systems for a building: electric boiler, cogeneration, biomass/wood, ground source water to water heat pump, heat pump borehole/glycol, standard boiler and solar collector. The results showed that the heat pumps have the highest exergetic and sustainability index after the solar collector. Thus, the researchers who relied on exergy analysis think that the heat pump is the appropriate heating system when compared with the other conventional heating systems which depend on fossil fuels, but the researchers who relied on LCA have a different view.

Shah et al. [7] compared the life cycle impact of three heating systems: a warm-air furnace, a hot water boiler and an air to air heat pump over a study period of 35 years. The LCA was studied for four different locations in the United States which differ in climate, energy mix, and standard building characteristics. The results showed that the heat pump has the highest environmental impact in three out of four locations. Greening and Azapagic [8] compared three different heat pumps using different energy sources with a gas boiler in the UK using LCA. The results showed that heat pumps have higher environmental impacts than gas boilers. This difference in results did not come as a surprise because each analytic tool performs the considered system from its perspective without considering the other perspectives, e.g. exergy analysis cannot distinguish between the electricity produced from wind energy and that produced by hard coal composition energy, while LCA can easily distinguish between them. Therefore, combining these two different tools within one combined method has large potential to make use of the strengths while reducing the weaknesses of the individual tool especially in HVAC applications. Thereby the methodological approach for a specific research question can be adapted and improved [9]. Combining the LCA and exergy analysis tools generates the advantage of giving a strategic overview of the thermodynamic life cycle performance of a product. Internal and external inefficiencies and improvement potential can be evaluated on a life cycle scale.

In this study, the heating energy from two conventional heating systems were compared with a ground source heat pump in terms of combined exergy analysis and LCA using an exergoenvironmental method. Exergoenvironmental analysis states that exergy is the only rational basis for assigning environmental impact to energy streams and to the thermodynamic inefficiencies within a system. The main objective of this study is to make a search for the best heating system which helps Turkey in its roadmap to use energy efficiently and to make a contribution to reducing the environmental burden during the next period. This study is the first such study for Turkey to the best of the authors' knowledge.

## 2. Heating systems descriptions

### 2.1. Conventional coal fired boiler

In this system all energy losses from the building and the components of the secondary heating system are meted out by conventional coal fired boiler. The conventional boiler with a thermal efficiency of 80% turns the chemical energy stored in the coal into thermal energy. The produced energy within the boiler is transferred to the heating emission within the building by water as an energy carrying medium through two well insulated piping network lines. The required energy is transferred to the conditioned space by high temperature panel radiators as illustrated in Fig. 1. The remaining energy is dispersed through the building envelope to the environment.

### 2.2. Natural gas fired boiler

The heating principle in this alternative is similar to the conventional coal boiler heating alternative, which uses a closed hot water-loop heating system, as illustrated in Fig. 2. In this system instead of a conventional boiler, a condensing boiler with a thermal efficiency of 95% is used to turns the chemical energy stored in the fuel, natural gas, into the thermal energy. In this type of boiler the flue gas is used to preheat the circulation water in order to increase