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Exergetic cost analysis and sustainability assessment of various low exergy heating systems

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ABSTRACT

This study deals with energy/exergy, exergy cost analyses and sustainability assessment of a low exergy heating system. In this study, an indoor sports hall with a volume of about 28,180 m^3 and a floor area of 2366 m^2 is considered as a case study. In this context, three different heating options are investigated, namely, (i) a conventional boiler, (ii) a condensing boiler and (iii) an air heat pump as driven by fuel-oil, natural gas and electricity, respectively. In this regard, an energy and exergy analysis is employed to assess their performances and compare them through energy and exergy efficiencies and sustainability index. Also, total exergy costs based on the considered systems with three different fuels are determined and compared with each other. Overall exergy efficiencies of the heating systems are found to be 2.10%, 2.33% and 2.42% while their corresponding sustainability index values of the analyzed cases are calculated to be 1.021, 1.024 and 1.025 for cases 1 through 3, respectively. Total exergy costs of the considered systems are obtained to be $C_{case1} > C_{case3} > C_{case2}$. Based on the exergy cost analysis results, the most cost effective system is Case 2.

1. Introduction

Global consumption of primary energy to provide space heating/cooling, lighting and other building-related energy services grew up due to growth in population, urbanization and industrialization. These appliances are the main part of the energy consumption in buildings which plays an important role in consumption of energy all over the world. Unfortunately, non-renewable energy sources or electricity, which is mostly generated by fossil fuels provide for these purposes. In this regard, the building sector has a great potential, for improving the quality match between energy supply and demand because high temperature sources are used to low temperature heating needs [1]. Nowadays, most of the energy is used for keeping our living and working spaces at comfortable temperatures to provide better environment. However, low efficient equipments are still used for these purposes [2,3]. Therefore, energy utilization in an efficient way for space heating and cooling is very important for the development of the energy systems [4]. Although, excessive utilization of non-renewable energy sources leads to several environmental issues, such as acid rain, global warming, ozone depletion due to an intensive increase in the level of carbon emissions.

The scope of this study is how to constitute a sustainable built environment. Nowadays, local initiatives and many researchers have been conducted on to develop new methodologies to analyze the energy demand of the buildings. Exergy concept as a significant tool can help achieve this objective. In fact, exergy is a long forgotten concept in building and HVAC technology so much so that energy balances are made by the first law of thermodynamics, which states that energy is neither destroyed nor created under this conservation law [5–7]. Simply, exergy can be defined as potential or quality of energy. Exergy is a suitable scientific concept for optimizing the building energy demand, towards sustainable development. Therefore, exergy analysis is very essential in improving efficiency that allows society to maximize the benefits. Rosen et al. [8] recommended that exergy concept should be applied by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies. In this regard, exergy analysis approach for buildings, which is so-called "Lowex (low exergy)" analysis approach, aims to understand the exergy flows in buildings, while it indicates the potential for further improvements in the energy utilization [7]. Schmidt [9] studied on design, optimization and performance assessment of the buildings using low exergy concept. In this regard, a new methodology for prediction models of the thermal behavior of the building components was derived [1]. One of the other important studies was on exergy efficient building design by Sakulpipatsin [10], who applied the exergy concept to the building and its service design.

In the literature, several studies have been undertaken on exergy analysis of various low exergy heating and cooling systems. Hepbasli [1], comprehensively reviewed and compared the studies on

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Nomenclature

A	area (m^2)
C	cost (TL/year)
$\dot{E}$	energy rate (W)
$\dot{E}x$	exergy rate (W)
f	approximation factor (–)
F	factor (–)
k	inverse of exergy efficiency (–)
no	number
P	power (W)
$\dot{Q}$	heat transfer rate (kW)
SI	sustainability index (–)
T	temperature (°C or K)
t	working hours (h/year)
U	thermal transmittance (W/m^{2}K)
V	volume (m^3)
z	cost of the fuel (TL/kWh)

Greek letters

η	energy efficiency (–)
ψ	exergy efficiency (–)
Δ	difference (–)
ρ	density (kg/m^3)

Subscripts

air	indoor air
aux	auxiliary energy requirement
dest	destruction
dis	distribution system
dt	design temperature
e	equipment
el	electricity
env	environment
flex	flexibility
HP	heat production system
HPP	heat production system position
HS	heating system
h	heat
heat	heater
i	indoor, counting variable
in	input, inlet
ins	insulation
l	lighting
loss	thermal losses
N	netto
o	outdoor, occupants
p	primary energy
pa	per area
plant	plant
pv	per volume
q	quality
R	renewable energy
ref	reference
ret	return
S	solar
s	source
sys	system
T	transmission
td	temperature drop
tot	total
V	ventilation

Superscripts

over dot rate (quantity per unit time)

Abbreviations

COP	coefficient of performance
DHW	domestic hot water
ECBCS	Energy Conservation in Buildings and Community Systems Programme
IEA	International Energy Agency
Lowex	low exergy

low exergy heating and cooling systems through exergy efficiency. Various exergy definitions were given in detail in Ref. [1].

Studies on lowex heating and cooling systems have been conducted by several authors [1,5–7,9–17]. The present study differs from the previously undertaken ones due to the facts that there are not any studies combining "exergy cost" and "lowex heating and cooling systems" in the open literature to the best of the author's knowledge. This was a key motivation behind the present study.

The exergy cost analysis, which is based on the exergy, gives better perspective on the energy systems. It also presents the true picture of the production cost of a process. In the recent years, various exergy-based economic analysis methodologies have been used by many investigators [18–21].

In this paper, exergy and cost analysis methods based on thermoeconomics and sustainability assessment through exergetic efficiency are applied to a low exergy heating system from the power plant through the heat production system and to the building envelope. The main objectives of the present study, which includes three options, namely (i) a conventional boiler, (ii) a condensing boiler and (iii) an air heat pump, are to determine their overall energy and exergy efficiencies and to define exergy costs for three cases, which are driven by three different fuels for comparing them with each others.

2. Methodology used

Energy and exergy analyses of the considered systems are evaluated by an Excel tool, which has been developed within the framework of International Energy Agency (IEA) formed within the Energy Conservation in Buildings and Community Systems Programme (ECBCSP) Annex 37 [22]. The tool and the calculation approach follow the method developed by Schmidt [5].

In the first section, the general project data and boundary conditions are checked out. V and A_N are the internal volume of the building and the net floor area, respectively. T_o is the outdoor temperature and T_i is the indoor temperature in the design conditions. The outdoor temperature is taken as the reference temperature T_{ref} for analysis purposes. Some necessary building specifications are given in Table 1.

The heat loss through the building envelope can be divided into two groups, namely, (i) The total transmission heat loss rate (with neglected thermal bridges), (ii) the ventilation heat losses rate.

Table 1
Some specifications of building.

Description	Value	Building part	U (W/m^2 K)
Volume	28,180 m^3	Exterior walls	0.77[a]
Floor area	2366 m^2	Door	2.91[a]
Window area	148.47 m^2	Window	2.60[a]
Door area	122.72 m^2	Floors to ground	0.42[a]
		Roof	0.44[a]

[a] Adapted from Ref. [23]