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Performance and sustainability assessment of energy options for building HVAC applications

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ABSTRACT

In this study, a building with a volume of 351 m^3 and a net floor area of 117 m^2 is considered as a case study with the indoor and exterior air temperatures of 20 and 0 °C, respectively. For the heating applications, four options are studied with (1) a heat pump, (2) a condensing boiler, (3) a conventional boiler and (4) a solar collector, which are driven by renewable and non-renewable energy sources. An energy and exergy analysis is employed to assess their performances and compare them through energy and exergy efficiencies and sustainability index. Energy and exergy flows are investigated and illustrated. Also, the energetic and exergetic renewability ratios are utilized here along with sustainability index. The results show that overall exergy efficiencies of heat pump, condensing boiler, conventional boiler and solar heating systems are found to be 3.66, 3.31, 2.91, and 12.64%, while the sustainability index values for the four cases considered are calculated to be 1.039, 1.034, 1.030 and 1.144, respectively. So, solar collector-based heating system gives the highest efficiency and sustainability index values.

1. Introduction

Energy consumption in the residential sector is one of the main parts of the total energy consumption in most countries. World-wide energy consumption by HVAC equipment in buildings ranges 16–50% of total energy consumption, depending on the countries and their sectoral energy use patterns, as shown in Fig. 1. More than half of this energy is typically used for heating [1]. Trends in energy demand for heating and cooling could, therefore, be very important for the development of the energy system. Of course, the key issue is how to make buildings energetically sustainable? Exergy as a thermodynamic analysis tool can help achieve this objective. The low exergy (LowEx) approach is one of these approaches, which may be used in sustainable buildings design.

The low exergy approach is the main object to constitute a sustainable built environment. Future buildings should be planned to use sustainable energy sources for HVAC applications. One characteristic of these energy sources is that only a relatively moderate temperature level can be reached, if reasonably efficient systems are desired [3].

Today, all estimations of the energy use in buildings, i.e., calculations of heating and/or cooling loads of rooms and buildings, as well as temperature calculations, are based on so-called energy balances. This is in reference to the first law of thermodynamics, which states that energy is neither destroyed nor created under this conservation law. To better understand the nature of energy flows in systems, we need to use the concept of exergy in addition to the energy [4,5].

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems. The aim of this method is to attain more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. Therefore, exergy analysis can reveal whether or not, and by how much, it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems [6]. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. And also they suggest that exergy approach should be applied by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies [7].

In the last few years, also due to the increasing interest in low temperature heating and high temperature cooling systems, a research co-operation in a working group of the International Energy Agency (IEA) has been formed within the Energy Conserva-

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.

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Nomenclature

A	area (m^2)
c_p	specific heat at constant pressure (kJ/kg K)
$\dot{E}$	energy rate (W)
$\dot{E}x$	exergy rate (W)
f	approximation factor
F	factor
g	total transmittance
I	radiation intensity (W/m^2)
l	length (m)
N	percentage of equipment resistance
n_d	air exchange rate (1/h)
no	number
P	power (W)
p	specific power, pressure (W/m^2, N/m^2)
$\dot{Q}$	heat transfer rate (kW)
R	pressure drop of the pipe (Pa/m)
R_R	renewability ratio
SI	sustainability index
T	temperature (K)
U	thermal transmittance (W/m^2 K)
$\dot{v}$	volumetric flow rate (m^3/s)
V	volume (m^3)

Greek letters

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

Subscripts

air	indoor air
aux	auxiliary energy requirement
circ	circulation
dis	distribution system
dt	design temperature
En	energetic
Ex	exergetic
e	equipment
el	electricity
env	environment
ex	external
f	window frame, parameter
Ge	generation
gp	generator position
HS	heating system
h	heat
heat	heater
i	indoor, counting variable
in	input, inlet
ins	insulation
j	counting variable
l	lighting
loss	thermal losses
max	maximum
N	netto
no	effect of non-orthogonal radiation
o	outdoor, occupants
p	primary energy
plant	plant
q	quality
R	renewable energy
ref	reference
ret	return
S	solar
s	source
sh	shading effects
T	transmission
td	temperature drop
tot	total
usf	useful
V	ventilation
w	window
x	part *x*

Superscript

over dot	rate

tion in Buildings and Community Systems Programme (ECBCSP): "Low Exergy Systems for Heating and Cooling of Buildings" [8]. However, the number of studies on exergetic analysis of LowEx heating systems is relatively low. In the literature, there are a few studies conducted on LowEx heating systems [5,9–19], and some recent ones are herewith summarized below:

Balta et al. [5] evaluated a low exergy heating system from the power plant through the ground-source heat pump to the building envelope and showed that the total exergy input rate is 7.93 kW with the largest exergy destruction rate of the system occurred in the primary energy transformation as 5.31 kW.

Shukuya and Hammache [17] compared three numerical examples of exergy consumption during the whole process of a space heating from the power plant, through the boiler to the building envelope in the steady state. Exergy analyses were conducted for three cases. About 30 case studies of LowEx buildings from 11 countries were presented in the Lowex guidebook [18].

Shukuya [19] described an exergetic approach for better understanding of the built environment, under the low-exergy systems for heating and cooling in future buildings. He concluded that air source heat pump is basically a device to separate exergy supplied by electricity into warm, cool and dry exergies, and that 85–88% of exergy supplied is necessarily consumed to produce the sum of cool and warm exergies.

The main objective of the present study is to conduct on energy and exergy analyses of four heating options [(i) a heat pump, (ii) a condensing boiler, (iii) a conventional boiler and (iv) a solar col-

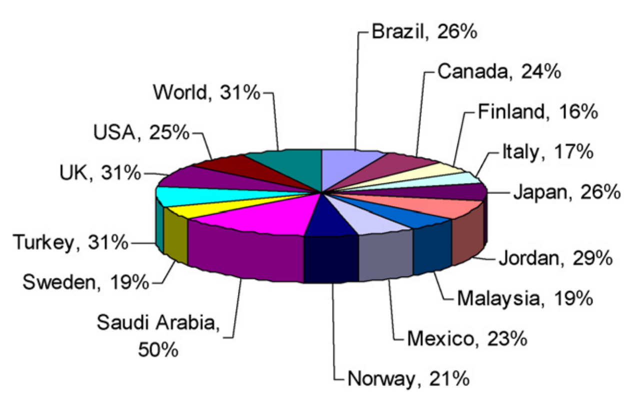

Fig. 1. Worldwide residential energy consumption (adopted from Ref. [2]).