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Exergy analysis of a two-stage ground source heat pump with a vertical bore for residential space conditioning under simulated occupancy ☆

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HIGHLIGHTS

- Exergy and energy analysis of a vertical-bore ground source heat pump over a 12-month period is presented.
- The ground provided more than 75% of the heating energy.
- Performance metrics are presented.
- Sources of systemic inefficiency are identified and prioritized using Exergy analysis.
- Understanding performance metrics is vital for judicial use of renewable energy.

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ABSTRACT

This twelve-month field study analyzes the performance of a 7.56 W (2.16-ton) water-to-air-ground source heat pump (WA-GSHP) to satisfy domestic space conditioning loads in a 253 m^2 house in a mixed-humid climate in the United States. The practical feasibility of using the ground as a source of renewable energy is clearly demonstrated. Better than 75% of the energy needed for space heating was extracted from the ground. The average monthly electricity consumption for space conditioning was only 40 kW h at summer and winter thermostat set points of 24.4 °C and 21.7 °C, respectively. The WA-GSHP shared the same 94.5 m vertical bore ground loop with a separate water-to-water ground-source heat pump (WW-GSHP) for meeting domestic hot water needs in the same house. Sources of systemic irreversibility, the main cause of lost work, are identified using Exergy and energy analysis.

Quantifying the sources of Exergy and energy losses is essential for further systemic improvements. The research findings suggest that the WA-GSHPs are a practical and viable technology to reduce primary energy consumption and greenhouse gas emissions under the IECC 2012 Standard, as well as the European Union (EU) 2020 targets of using renewable energy resources.

1. Introduction

While the ultimate impact of climate change may be difficult to quantify, scientific evidence suggests a causal relationship between greenhouse gas emissions and its effects on global warming trends, food production, frequency and severity of weather patterns, water shortages, diseases, and environmental stress for flora and fauna [1]. Approximately 33% of total global greenhouse gas emissions come from buildings as a result of fossil fuel consumption for their operation [1]. In the United States, the buildings sector accounted for about 40.7% of primary energy consumption in 2013, compared to 30.5% for industry, and 28.5% for transportation [2]. In the European Union (EU), buildings represent approximately 40% of the EU's energy consumption and carbon dioxide production [3].

The trends in coal, oil, and natural gas consumption and the emissions of greenhouse gases from combustion and other sources such as refrigerants are deemed unsustainable. Options for reducing fossil energy consumption include the use of renewable energy for producing electricity and thermal energy, summarized in a report, "Renewable Energy Sources and Climate Change Mitigation" by the Intergovernmental Panel on Climate Change [4]. Although in 2008, renewable energy contributed about 21%

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Nomenclature

Quantities

ACH	Air Changer per hour (dimensionless)
ASHRAE	Amer. Soc. Heating Refrigeration and Air-Conditioning
CDD	Cooling degree days, °C-days or °F-days
COP	Coefficient of performance (dimensionless)
CT	Current Transformer
CV	Control Volume or System Boundary
DOE	U.S Department of Energy
EER	Energy Efficiency Ratio, (dimensionless)
EU	European Union
EWT	Entering Water Temperature, °C
FS	Full Scale
GLHX	Ground Loop Heat Exchanger
GSHP	Ground Source Heat Pump
g	gravitational acceleration (m s^{-2})
h	enthalpy (kJ kg^{-1})
HDD	Heating Degree Days, °C-days or °F-days
HERS	Home Energy Rating System
$\dot{I}$	rate of thermodynamic irreversibility (W)
I	irreversibility (kW h)
LWT	Leaving Water Temperature, °C
$\dot{m}$	mass flow rate (kg s^{-1})
Mtoe	Million tons of oil equivalents
OEM	Original Equipment Manufacturer
P	pressure (kPa)
PCM	Phase change material
$\dot{Q}$	thermal energy flow (W)
QSSSF	Quasi Steady-State-Steady-Flow process
R_{SI}	*R*-value of insulation in SI
R_{US}	*R*-value of insulation in English units
s	entropy (kJ kg^{-1} K^{-1})
SSSF	Steady-State-Steady Flow process
SHGC	Solar Heat Gain Coefficient, (dimensionless)
T	temperature (K)
U	internal energy (kJ kg^{-1})
V	velocity (m s^{-1})
$\dot{W}$	rate of work (W)
WA-GSHP	Water-to-air ground source heat pump
WW-GSHP	Water-to-water ground source heat pump
%Δ	percent deviation
η	efficiency (dimensionless)
$\dot{\sigma}$	rate of entropy generation (W K^{-1})

Subscripts

Comp.	Compressor
discharge	compressor discharge port
o	dead state corresponding to the surroundings
j	thermal reservoir other than the dead state
EWT	entering water temperature (°C)
Brine HX	*brine heat exchanger*
Indoor HX	Indoor refrigerant-to-air heat exchanger
suction	compressor suction port
Fans+Controls	fans and electronic controls on electronic boards
pump	brine pump
e,Aux	electrical energy of the auxiliary heating element
GLHX	ground loop heat exchanger
e,Total	total electrical energy
Total	aggregate sum of the elements under consideration

of the global electricity supply (16% hydroelectric, 3% other renewable energy, 2% biofuels of global transport fuel supply), both solar thermal and geothermal energy accounted for only 2% of the total global demand for heat [4,5].

The buildings sector in the U.S. consists of 5 million commercial buildings and 115 million residential households, consuming 6×10^{12} kW h, approximately 40% of the total U.S. energy demand (11×10^{12} kW h) [6,7] in 2013. There is an abundance of thermal energy in the ground that can be used for space and water heating, even from shallow sub-surfaces [8,9]. With growing demand for space conditioning, and the parallel need to decrease fossil energy consumption, researchers are looking at various hybrid options such as hybridizing ground source heat pump (GSHP) systems with auxiliary systems [10,11].

A comparison of ground-source heat pump technology versus conventional heating systems in terms of costs and carbon dioxide emissions showed GSHPs to be a cleaner and practical alternative [11]. Comparison of ground source heat pumps with other heating systems is evaluated by Self et al. [12]. The energy savings by deploying water source heat pumps in an apartment complex with eighty-seven apartments each with 949 m^3 conditioned floor space was reported by Chen et al. [13]. Estimates of energy and CO_2 saving with GSHPs in 10 states in India are summarized by Sivasakthivel et al. [14]. Globally, interest in using the ground as a thermal energy resource is increasing. Among the 28 EU countries alone, approximately 260 million tons of oil equivalent (Mtoe) is emitted annually from land surfaces [15], signaling a huge potential energy resource.

Recently, Exergy analysis of a three-circuit vertical ground-loop with two GSHPs [16] with total cooling and heating capacities of 1324 kW and 1458 kW, respectively installed for a 14,000 m^2 hotel building showed that the greatest Exergy penalty occurred in the compressor and the ground loop. Also, Exergy losses in the heating mode were higher than in the cooling mode. In laboratory testing of GSHPs with R134a [17] during the heating months from January-May showed that residential heating could be done in Erzurum, one of the coldest climatic regions in Turkey, with heating COPs in the range of 2.07–3.04. Energy analysis of other vertical-bore heat pump systems using R-22 and R-134a have been reported by [18–20], respectively. Healy and Ugursal [21] investigated computationally the feasibility of using a GSHP in place of a conventional heating (gas furnace) and cooling (air-source heat pump) system and concluded that although system parameters have a significant effect on performance, the GSHP is economically preferable to conventional systems in certain Canadian climates. They report that a typical GSHP has a COP of 2.9–3.2 at 2 °C EWT whereas, all the conventional systems have lower COPs. For example, resistance heaters have a COP of 1; oil heating a COP between 0.65 and 0.7; and a high efficiency natural gas furnace, a COP between 0.8 and 0.95. The COP of an air-source heat pump is also lower than that of the GSHP given the fact that during winter, the air temperatures in Canada are much lower than the ground temperatures. Their modeling estimated that the GSHP may provide 65–70% energy savings relative to the conventional systems.

A meticulous examination of the practicality of using the ground as a source and sink for thermal energy transfers in space conditioning applications is deliberated in this paper. Although thermal energy from the ground is readily available as a renewable resource, its practical use, even in developed economies, is not yet widespread. In this paper we provide metrics to show that by using the ground as a thermal source for space heating, a large fraction of the space heating load can be extracted from the ground. In space cooling, the ground acts as a thermal sink. During the 12-month