Geothermal Energy

Subjects: Energy & Fuels | Engineering, Civil
Contributor: Andrea Aquino

Geothermal heat have a widespread diffusion as they are able to deliver relatively higher energy output than other systems for building air-conditioning. The exploitation of low-enthalpy geothermal energy, however, presents crucial sustainability issues.

geothermal heat pumps sustainability LCA

1. Introduction

Heat Pumps (HPs) for building air-conditioning are having a wide diffusion worldwide. For instance, the statistics from the European Heat Pump Association (EHPA) report an uninterrupted growth of the HP installations in the European Market from 2012, leading to a total installed capacity of 10.6 million units in 2017; at this rate, the European HP market will double by 2024 [1][2]. The popularity of HPs depends on their energetic and environmental benefits [1]:

- HPs consume electricity to extract heat from a low-temperature source and produce higher-temperature thermal energy. According to the nature of the colder source, the generated heat is about 2–4 times greater than the consumed electricity, and therefore, most of the output energy is renewable.

- HPs produce thermal energy with high efficiency. Nowak [1] compare the energy demanded to produce a thermal energy unit by HPs and traditional fossil fuels systems; their results show the HPs more efficient than conventional heating systems up to four times; similar benefits also emerge in terms of CO

- emissions per produced kWh that can be three times lower than fossil-fueled heating systems.

Ground-source heat pumps (GSHPs) use solar energy stored in the first layers of the ground, which is available as a low-temperature energy source all year long. Torio et al. [3] indicate the GSHPs as particularly convenient in terms of energy and exergy efficiency among the available renewable energy systems for building air-conditioning. Furthermore, the feasibility of such systems does not depend on the nature of the geothermal source at the site. Since the low operative temperatures involved in its thermodynamic cycle (5–30

C [4]), a GSHP system exploits the shallow layer of the ground, and it could theoretically be installed worldwide (the maximum layer depth involved in the heat exchange generally ranges between 20 and 200 m [5]). We remand further technical details on the Heat-Pump (HP) thermodynamics. Market statistics highlight the benefits presented above: the installed capacity of geothermal heat pumps increased from 2000 to 2009 by 6.28 times [6], and the latest report by Lund and Toth [7] indicate the worldwide yearly exploitation of geothermal energy by heat pumps increased by three times from 2010 to 2020.

2. Life-Cycle Impact Assessment of Shallow Geothermal Energy

In its classic applications, geothermal energy exploitation is not one of the best performing technologies in environmental terms among all the renewables, showing the highest impact values in several environmental indicators compared to the other technologies [8]. However, many environmental impact studies available in the literature indicate the low enthalpy, namely, the shallow geothermal energy exploited by GSHP as key renewable sources for sustainable heating and cooling applications.

Reddy et al. [9] presented a comparative sustainability assessment—using LCA to evaluate the environmental impacts—of geothermal and conventional systems used in three different buildings in the United States and concluded that from the environmental, economic, and social point of view, the geothermal system is more sustainable than the conventional one. Furthermore, regarding the environmental impact, the geothermal system showed a better performance in all the ten impact categories considered, with a reduction in climate change impact in the order of 80 to 90%.

Pratiwi and Trutnevyte [10] calculated the life cycle impacts of different (six, hypothetical) heating and cooling configurations from shallow to medium-depth geothermal wells with connected, decentralized heat pumps and district heating and cooling in Switzerland (State of Geneva), comparing them with other heating and cooling sources to evaluate their advantages and disadvantages in terms of environmental impact. They evaluated eight environmental impact indicators and observed that geothermal heating systems are generally environmentally preferable, even if, in some cases, geothermal heat could have more significant impacts than fossil fuels. In particular, Pratiwi and Trutnevyte [10] showed that geothermal systems could have higher impacts, among the various indicators, both in terms of water consumption and land use. In this regard, they estimated water consumption values ranging from 57 to 81 m /MWh and land use values ranging from 0.2 to 0.44 m year crop eq/MWh for the analyzed configurations. They also found that the environmental impacts of a given geothermal resource are lower when installing decentralized connected heat pumps in place of traditional district heating and cooling. Moreover, combining shallow wells with connected decentralized heat pumps seems to lower the impacts further.

Therefore, environmental studies focused on shallow to medium-depth geothermal heating and cooling are desirable to obtain a complete picture of exploiting the geothermal energy for building air-conditioning. Moreover, to properly assess the sustainability of geothermal systems used for building air-conditioning, the evaluation should focus on a broader range of environmental indicators, since potential interactions with other environmental spheres —such as underground and groundwater—may occur and be quantifiable ([11][12]).

3. Thermodynamic Cycle and Efficiency

The thermodynamic cycle of a heat pump consists of transferring heat from a cold to a hot source using the work of a compressor (**Figure 1**). Standard systems operate a Rankine inverse vapor-compression cycle. The cycle starts in the evaporator, where the low-temperature heat ($\dot{Q}_L$), withdrawn from the cold source, heats the refrigerant to the saturation state. The compressor overheats the refrigerant by the input work ($\dot{W}$) and flows it to the condenser, where the heat-transfer fluid of the hot source receives the whole output heat:

$$(1)\ \dot{Q}_H = \dot{W} + \dot{Q}_L.$$

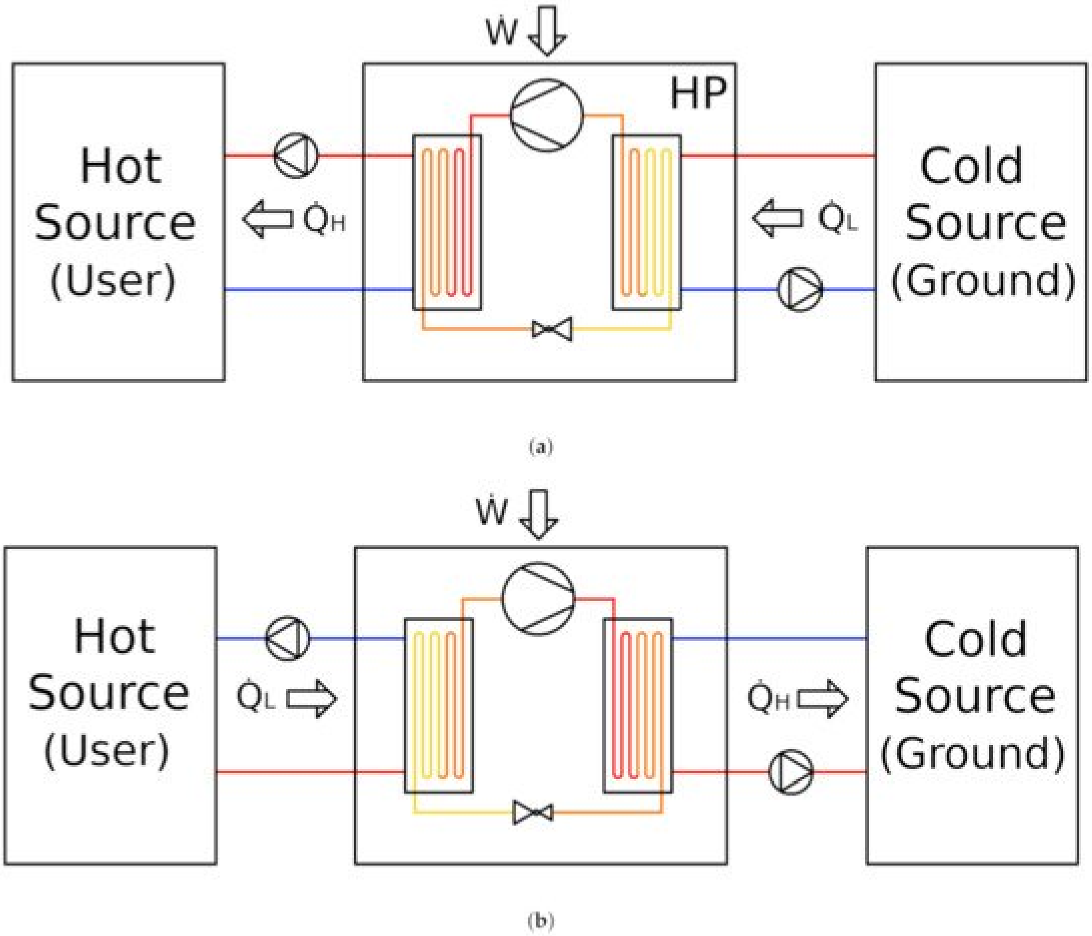

Figure 1. Ground-source heat pump working cycles in heating (**a**) and cooling (**b**) mode.

The exhaust refrigerant returns to the evaporator through a throttling valve, which reduces the pressure and temperature to the level of the evaporator (i.e., throttling process), and the cycle restarts. When used for space heating, ground-source heat pumps for air-conditioning transfer heat from the shallow layer of the ground (cold source) to the building space (hot source, see **Figure 1**a). In cooling mode, the cycle is reversed (i.e., evaporator and condenser are switched), and the GSHP uses the ground (cold source) to dissipate the excess heat (**Figure 1**b).

The Coefficient of Performance (COP) is an index used to quantify the heating performance of an HP. It is defined as the ratio of the total output heat over the work by the compressor, and it is related to the efficiency of the cycle:

$$(2) \quad COP = \dot{Q}_H / \dot{W}.$$

It is straightforward to see that the work of the compressor adds up to the heat extracted from the ground (see Equation (1)). The performance of an HP used in cooling mode is commonly described by the Energy Efficiency Ratio (EER), defined as the ratio of the heat subtracted from the building to the external work:

$$(3) \quad EER = \dot{Q}_L / \dot{W}.$$

In this case, the work of the compressor does not sum up in the numerator of the performance index. Having remarked such a difference between the two indices, it is somehow common to only refer to COP even when assessing the cooling performance of an HP. The cooling COP has to be calculated according to Equation (3).

3.1. Energy

The European Directive 28/2009 defines heat pumps as renewable systems only if the heat supplied to the user significantly exceeds the consumed energy over the whole climatic season (yearly averaged COP ≥ 1.5), de facto making the COP the first indicator of the sustainability of a heat pump system. The European Code 14511:2018 indicates to manufacturers the standard conditions for the COP calculation and prescribes to include the electrical needs of auxiliary devices and circulation pumps in the input energy (W). However, the assumption of a constant COP presents poor accuracy, especially in long-term analysis, since the operating conditions that influence the COP change along the operating cycle. Furthermore, the continuous heat extraction from the ground changes its temperature with consequent degradation of the system performance over the long period.

Several works investigate the relations between the GSHP operating conditions and COP. For example, Sivasakthivel et al. indicate the heating load, water temperature from the cold source, the thermal conductivity of heat exchanger pipe material, and mass flow rate of fluid per kW of load as the main parameters affecting the COP with variations of ±26%.

Staffell et al. derive the following empirical relation, specific for domestic heat-pump, based on data from manufactures:

COP=0.000734·ΔT2−0.15·ΔT+8.77

$$(4) \quad COP = 0.000734 \cdot \Delta T^2 - 0.15 \cdot \Delta T + 8.77$$

The temperature difference between the average temperature of the water entering and leaving the condenser and evaporator (ΔT) should be between 20 and 60∘C.

Figueroa et al. apply a model predictive controller methodology to a GSHP system. They model the COP by non-linear equations, including the inlet and outlet temperatures of the ground and variable mass flow rates of the heat transfer fluid. Results show that enhancing the accuracy of the COP model increases the economic savings from 0.46% to 2.71%, depending on the electricity-to-gas price ratio scenario.

Ommen et al. propose a COP prediction model for HP in industrial applications, which includes three main groups of variables representing the (i) the inlet and outlet temperature from the cold source, (ii) component-specific parameter (e.g., the compressor efficiency), and (iii) the characteristics of refrigerant.

Pieper et al. model the COP of an HP for district heating at off-design conditions by linear correlations. They estimate an offset of the COP between the design and off-design conditions, including the temperature of the cold source and the user’s temperature.

Qian and Wang model the heat transfer around a vertical boreholes field and calculate the COP by the soil temperature distribution. The latter depends on the soil thermal properties, the distance between the boreholes, cooling and heating loads, and ambient air temperature. Results show accurate predictions for balanced heating and cooling loads. Furthermore, the irregular cycles facilitate the soil temperature recovery, and therefore, these present higher COPs than full-day operations.

The energy analysis is the standard approach to formulate COP prediction models. However, the analysis of system performance limited to energy flows does not distinguish the quality of energy inputs and is independent of the environmental conditions. Thus, such an approach may result inaccurate to evaluate the impacts of the system on the environment.

3.2. Exergy

Exergy analysis studies entropy generation in heat exchange and conversion processes. The review by Lucia et al. [13] resumes the thermodynamic assessments of GSHP systems available in the literature. Based on studies following the entropy minimization criteria, authors estimate a seasonal average exergy efficiency around 68% (with further optimization potential), and achievable savings on installation costs by 5.5%.

The exergy efficiency is the ratio of the output to input exergy flows [13] and the exergy loss represents the amount of exergy destroyed in each component by the entropy generation [14]. The exergy analysis of a GSHP measures its performance considering the quality of the energy flows and their relation with the environment (i.e., dead-state) [15]. Such an approach quantifies the entropy generation of a GSHP system: it indicates the potential energy savings of each component and distinguishes the different impacts of the system on the environment.

The pioneering study by Hepbasli and Akdemir [16] presents the energy and exergy analysis of a GSHP system with vertical boreholes. Results show the highest entropy generation in the compressor due to electrical, mechanical, and isentropic inefficiencies. The irreversibility of the condenser depends on the super-heating of refrigerant in the compression process, producing a significant temperature difference from the evaporation point. The third-highest entropy generation is in the expansion valve because of the pressure drop.

Akpinar and Hepbasli [17] study the exergy performance of two GSHP systems installed in Turkey based on the actual operational data. The fist one is a GSHP system designed and constructed for investigating geothermal resources with low temperatures, while the second one is a GSHP system with a vertical ground heat exchanger (see Section 3.2). Results show the exergy efficiencies varying in the range from 0.0144 to 0.0384. The highest irreversibility is in the motor–compressor.

Bi et al. [18] calculates the exergy losses in all components of a GSHP system, distinguishing the cooling and heating mode. Results indicate the compressor and Ground Heat Exchanger (GHE) as the components with the most promising energy savings potential because these present the highest exergy destruction rate and the minimum exergy efficiency, respectively; exergy losses in heating mode are higher than cooling mode.

Li et al. [19] compare the exergy performance of a GSHP against an air-source heat pump system, distinguishing between the exergy flows from the system to the environment and vice versa, namely, warm and cool exergy. Results show that the exergy efficiency of the GSHP equals 19.1 and 19.9% when the system is operating in cooling mode and dehumidification mode, respectively, against the ASHP that presents an exergy efficiency of 9.3 to 11.9%, respectively. The performance of the GSHP is sensibly higher than the ASHP because of a more spontaneous heat transfer between the ground and cooling water: the temperature difference between the user and the cold source is smaller than in ASHP, and the ground temperature is generally lower than that of the ambient air. Similarly to [16][17][18], authors observe the highest exergy losses and improving potential in the compressor and refrigerant cycle.

References

1. Lucia, U.; Simonetti, M.; Chiesa, G.; Grisolia, G. Ground-source pump system for heating and cooling: Review and thermodynamic approach. Renew. Sustain. Energy Rev. 2017, 70, 867–874.
2. Morosuk, T.; Tsatsaronis, G. A new approach to the exergy analysis of absorption refrigeration machines. Energy 2008, 33, 890–907.
3. Rosen, M.A.; Dincer, I.; Kanoglu, M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 2008, 36, 128–137.
4. Hepbasli, A.; Akdemir, O. Energy and exergy analysis of a ground source (geothermal) heat pump system. Energy Convers. Manag. 2004, 45, 737–753.
5. Akpinar, E.K.; Hepbasli, A. A comparative study on exergetic assessment of two ground-source (geothermal) heat pump systems for residential applications. Build. Environ. 2007, 42, 2004–2013.
6. Bi, Y.; Wang, X.; Liu, Y.; Zhang, H.; Chen, L. Comprehensive exergy analysis of a ground-source heat pump system for both building heating and cooling modes. Appl. Energy 2009, 86, 2560–

2565.

7. Li, R.; Ooka, R.; Shukuya, M. Theoretical analysis on ground source heat pump and air source heat pump systems by the concepts of cool and warm exergy. Energy Build. 2014, 75, 447–455.