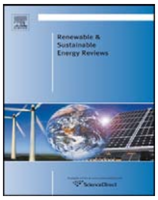
Renewable and Sustainable Energy Reviews 14 (2010) 1798–1813

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems

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ARTICLE INFO

Article history:
Received 2 February 2010
Accepted 26 March 2010

Keywords:
Geothermal heat pumps
Ground source heat pumps
Life cycle assessment
Climate change
Greenhouse gases
Electricity mix

ABSTRACT

Shallow geothermal systems such as open and closed geothermal heat pump (GHP) systems are considered to be an efficient and renewable energy technology for cooling and heating of buildings and other facilities. The numbers of installed ground source heat pump (GSHP) systems, for example, is continuously increasing worldwide. The objective of the current study is not only to discuss the net energy consumption and greenhouse gas (GHG) emissions or savings by GHP operation, but also to fully examine environmental burdens and benefits related to applications of such shallow geothermal systems by employing a state-of-the-art life cycle assessment (LCA). The latter enables us to assess the entire energy flows and resources use for any product or service that is involved in the life cycle of such a technology. The applied life cycle impact assessment methodology (ReCiPe 2008) shows the relative contributions of resources depletion (34%), human health (43%) and ecosystem quality (23%) of such GSHP systems to the overall environmental damage. Climate change, as one impact category among 18 others, contributes 55.4% to the total environmental impacts. The life cycle impact assessment also demonstrates that the supplied electricity for the operation of the heat pump is the primary contributor to the environmental impact of GSHP systems, followed by the heat pump refrigerant, production of the heat pump, transport, heat carrier liquid, borehole and borehole heat exchanger (BHE). GHG emissions related to the use of such GSHP systems are carefully reviewed; an average of 63 t CO_2 equivalent emissions is calculated for a life cycle of 20 years using the Continental European electricity mix with 0.599 kg CO_2 eq/kWh. However, resulting CO_2 eq savings for Europe, which are between −31% and 88% in comparison to conventional heating systems such as oil fired boilers and gas furnaces, largely depend on the primary resource of the supplied electricity for the heat pump, the climatic conditions and the inclusion of passive cooling capabilities. Factors such as degradation of coefficient of performance, as well as total leakage of the heat carrier fluid into the soil and aquifer are also carefully assessed, but show only minor environmental impacts.

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doi:10.1016/j.rser.2010.04.002

1. Introduction

Geothermal heat pumps (GHPs) have evolved as an attractive technology for space heating and cooling. It is predicted that worldwide use of such systems will exponentially increase in the next decades [1,2]. GHPs utilize the underground as a free geothermal energy reservoir or storage medium (e.g. aquifer thermal energy storage) and thus can be applied nearly everywhere, even in areas of low geothermal gradient. There are mainly two types of GHPs. In open systems such as groundwater heat pump (GWHP) systems, wells are installed and groundwater is used directly as heat carrier. However, much more common are closed systems (ground source heat pump, GSHP systems), where boreholes are equipped with pipes that act as borehole heat exchangers (BHEs). Energy transfer between the BHEs and the ground is established by circulating a synthetic heat carrier fluid. Before putting a GHP in operation, boreholes have to be drilled, extraction and injection wells or BHEs have to be installed in the ground. Furthermore, these devices have to be connected to the heat pump in the building. Commonly such boreholes reach shallow depths ($<$400 m). Deeper geothermal technologies such as enhanced geothermal systems (EGS) are more sizeable and are mainly installed for the generation of electricity (e.g. [3]).

As a low enthalpy system, a GHP continuously consumes primary energy for secondary energy production. The temperature of the heat carrier fluid is low grade and cannot reach values higher than the shallow ground. The heat pump extracts energy from the carrier fluid by compressing and evaporating a refrigerant. This is a critical step that costs energy, in most cases electrical power from the grid. The consumption of energy rises with the absolute increase a heat pump has to achieve from carrier fluid temperature to the desired space temperature. For quantifying the energy efficiency of GHPs, a seasonal performance factor (SPF) and a coefficient of performance (COP), which is the ratio between the the amount of heat delivered to a hot reservoir and the heat pump compressor's dissipated work, are commonly used. Typical reported values for COP range between 3 and 5 for temperature differences between 0 and 35 °C [4,5].

As indicated by the COP, geothermal heat can hardly be considered as fully renewable. In fact, this is also true for mining of alternative energy resources that are considered environmentally benign (e.g. [6]). However, for GHPs energy is consumed mainly during operation, in contrast to energy generation from solar or wind where manufacturing of equipment is most relevant [7,8]. For GHP systems, net greenhouse gases (GHG) emissions depend on the type of primary energy source for power supply, its demand and the relative amount of geothermal energy developed. Obviously, the environmental impacts of such different technologies are ideally compared by examining their entire life cycle instead of picking out particular stages (e.g. construction and disposal). This may be intricate, especially if distinct types of emissions are produced at different points in time, with their specific effects and if they are calculated in variable units.

In this study, we focus not only on the net energy consumption and greenhouse gas (GHG) emissions or savings by GHP operation, but adopt a life cycle perspective to fully examine the environmental burdens and benefits related to applications of shallow geothermal systems. A state-of-the-art life cycle assessment (LCA) framework is set up. This standardized evaluation method enables us to trace the entire energy flows and resources use for any product or service. All stages in a product's life, from extraction of natural resources and processing of raw materials, through production, distribution, use, to the final disposal, are taken into account. In such a cradle-to-grave approach, all up- and downstream inputs and outputs along all the phases of the life cycle are analyzed and evaluated. Until now, most studies exclusively rate environmental impact of GHPs only on its potential to save energy and hence greenhouse gas emissions [1,9–11]. Existing LCA concepts not only focus on issues related to energy flows and global warming, but also examine potential adverse effects on other environmental safeguard subjects such as depletion of ozone layer or land use [7,12,13]. This is also considered in this study and the relevance of these different impact categories for GHPs is elaborated.

In the following, a selective review of projects and studies on low-enthalpy geothermal heating systems is presented. Special focus is set on those that discuss the environmental performance or that define environmental indicators for the systems design. A range of different environmentally relevant factors and consequences are elaborated and then embedded into a LCA framework. We ask what role other environmental impact categories, besides climate change, play, and if they are appropriately reflected. This is answered by contrasting experience from previous studies with the results from LCA application to a typical GSHP system. The GSHP system supplies a single family house with a heating and cooling demand of 10 kW and 5 kW, and is investigated by several representative scenarios.

2. Related work

2.1. Carbon dioxide as proxy for environmental effect

In numerous studies on GHP applications, generated or saved GHG emissions are regarded as surrogate or proxy for environmental threat or benefit. For example, Lo Russo et al. [14] calculated significant potential savings in energy use and CO_2 emissions as a main argument for using low-enthalpy geothermal technologies for space heating and air conditioning in the region of Piemont, Italy. Blum et al. [9] studied the total CO_2 savings of vertical GSHP systems in a state in South Germany. They concluded that for the studied state the minimum resulting CO_2 savings for one installed GSHP unit (using a COP of 4) is about 1800 kg per year using the average CO_2 emission of the German electricity mix.

Akella et al. [15] identified social, economic and environmental impacts related to renewable energy systems in India, but exclusively ranked different technological options with respect to associated GHG emissions. Yasukawa et al. [16] provide an insight into the long-term prospects of the use of geothermal energy and their environmental effects in Japan. Three scenarios are presented to delineate possible increases of geothermal energy