Renewable Energy 76 (2015) 699–705

Contents lists available at ScienceDirect

Renewable Energy

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

Evaluation of the economic and environmental feasibility of heat pump systems in residential buildings, with varying qualities of the building envelope

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ARTICLE INFO

Article history:
Received 21 February 2014
Accepted 13 November 2014
Available online

Keywords:
Economic feasibility of heat pumps
Environmental feasibility of heat pumps
Life cycle cost heat pumps
Impact of insulation level to heat pump technology

ABSTRACT

In this study, the economic and environmental feasibility of air-to-air and geothermal heat pump systems is examined. The significance of the insulation level of the envelope on the economic and environmental feasibility of heat pump systems is demonstrated.

The goal of this study is to quantify the extent to which the local climate and the building insulation level influences the economic and environmental feasibility of a geothermal water-to-air heat pump system and an external air-to-air heat pump system.

In this study, the seasonal coefficient of performance SCOP is predicted for both heat pump systems for a residential building with varying insulation levels representative locations of the United States. The SCOP of both heat pump systems is calculated in a dynamic calculation process for use in a representative residential building with three different insulation levels of the building envelope.

Results show a huge sensibility of SCOP values and feasibility studies towards the insulation level of the building envelope and the location.

1. Introduction

In recent decades, experts have debated the economic and environmental feasibility of heat pump (HP) systems for room heating in residential houses. The use of this technology has increased despite of the lack of consensus among experts as to whether these systems are economically and environmentally feasible in all cases. The US Environmental Protection Agency (EPA) has estimated that the use of a geothermal HP system has the potential to reduce the energy demand for room heating by up to 72% compared to conventional heating and air conditioning systems [1]. The economic and environmental questions are, however, still being debated.

Previous discussions about HP systems have not fully taken into consideration the inter-related factors that affect the economic feasibility of different heating systems. Because of the relatively constant temperature in the ground, geothermal HP systems typically have a better performance than HP systems with external air as a primary heat source [2]. However, the implementation of geothermal heat pumps in locations with relatively low heating requirements might not be economically feasible, since the capital costs of these systems are significantly higher than air-to-air HP systems.

Similarly, the environmental feasibility of HP systems in different climate zones has not been completely established. The green house gas emission for building operation is commonly seen as an evaluation criterion for the environmental feasibility of HVAC systems [3]. Bayer et al. [4] analyzed the environmental feasibility of geothermal HP systems in European countries and found that the environmental feasibility of a HP system depends on its SCOP and the energy mix of the electricity generation in the country. In the US, the use of electricity is considered as a green house gas emission intensive energy source because it is largely based on coal combusting power plants [5]. A HP system with a relatively high SCOP as a result of being located in a warmer climate or in a well-insulated building might have a smaller green house gas emission than a gas firing conventional furnace system.

The insulation level of the building envelope, along with the climate, influences the seasonal coefficient of performance SCOP. A building with a higher insulation level has a shorter specific heating season than a building with a lower insulation level, which reduces the cost and green house gas emission for building operation. Also, smaller heating load values permit shorter vertical geothermal heat exchangers, which are significantly less costly than longer heat

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http://dx.doi.org/10.1016/j.renene.2014.11.037
0960-1481/

exchangers. Thus, an economic and environmental evaluation of HP systems will benefit from the inclusion of information about the building envelope and its effects on the SCOP values.

Francisco et al. estimated the impact of the climate, control strategies, and pipe sizing on the SCOP of HP systems and demonstrated the large impact of all three of these factors [6]. The researchers confirmed a huge influence of the climate on the SCOP values of the HP systems.

A geothermal HP system has been evaluated in five U.S. climates by Rice at al [7]. The study compared the performance of ground source HP systems with that of conventional systems. The researchers showed that the HP systems have higher efficiencies in all five climates. However, they do not discuss the economics or green house gas emissions.

Self et al. [8] compared two HP systems, with conventional heating systems in the cold climate of Canada. The researchers conclude that the geothermal HP technology is economically feasible in all regions studied. However, in this study, no climate and building specific analysis for the specific SCOP value of the HP systems was done.

Aste et al. [9] analyzed the economic and environmental feasibility of heat pump systems in different climate regions in Italy. The researchers stated that both HP systems can be a feasible solution but they did not analyze the influence of the insulation level of these systems.

No previous work has focused on the comparative economic and environmental feasibility of geothermal and air-to-air HP technologies in residential buildings with different quantities of insulation located in different climate regions. The goal of this study is to illustrate the economic and environmental feasibility of ground source water-to-air HP system and an air-to-air HP system for residential buildings with three different insulation standards. A typical single-family residential building is chosen as a test case [10]. In order to achieve a dense number of data for each climate, the feasibility is predicted for a large number (238) of locations in the US.

This study uses the thermal building simulation program Trnsys 17. In each simulation time step, the heating load and the control status of the heating system are used to calculate the actual coefficient of performance (COP) for each hour in the year. The computer simulation uses a bin method calculation to derive the SCOP values.

A benchmark analysis is used to compare the two HP systems to a furnace as the conventional heating unit.

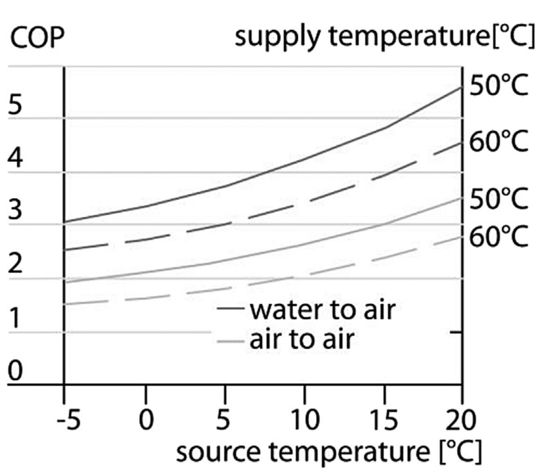

Fig. 1. COP values for the air-to-air and water-to-air heat pump in a function of the primary heat temperature.

Evaluation criterion for the economic evaluation is the Life Cycle Cost (LCC) analysis, which includes the net present value (NPV). LCC analysis has been used and proven as performance criteria in several studies [11,12]. Evaluation criterion for the environmental impact is the CO_2 emission for building operation.

2. Methods

2.1. Description of the heating systems

Three heating systems are compared in the study. Two heat pumps, an air-to-air HP system, and a geothermal HP system are compared with a conventional furnace system as a benchmark.

For the air-to-air HP, the external air is taken as a primary heat source. The geothermal HP system is equipped with a vertical heat exchanger. The length of the vertical heat exchanger and the SCOP is calculated for each of the three buildings and each climate. Fig. 1 shows the coefficient of performance (COP) as a function of primary heat temperature for each of the both HP types.

2.2. Simulation model of the HP

2.2.1. Dynamic calculation of the SCOP

To obtain the SCOP, the hourly coefficient of performance of the two HP systems is calculated in the simulation process. On the basis of the primary heat source temperature and the temperature of the heating coil in the mechanical ventilation, the COP is calculated by using the data in Fig. 1. The calculation method that was introduced by Li and Wu [13] and verified by Nigusse and Raustad [14] is used to calculate the COP for each hour with heating energy. Average curve fitting data reported by Nigusse and Raustad have been used to calculate the hourly COP value [15]. It should be noted that variations between heat pump types and manufacturers cause variation in the COP values. This variation is considered in a sensitivity study in Section 3.4. The energy demand for heating is calculated for each hour in the year and includes the operation time, the primary temperature and the output temperature of the heat pump. The SCOP is the statistical annual average of the hourly COP values. Fig. 2 is a working flow chart showing the SCOP is calculated.

Only time periods with heating demand and warm water demand are considered for the calculation. The performance of all three heating systems is calculated to cover the two usual cases, space heating and domestic warm water heating.

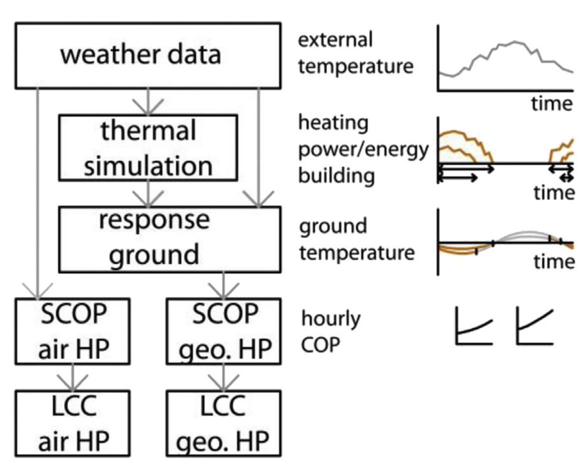

Fig. 2. Working flow diagram of the SCOP calculation.