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Analysis of the effect of global climate change on ground source heat pump systems in different climate categories

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ABSTRACT

Ground source heat pump (GSHP) systems exhibit high thermal performance. Consequently, they are increasingly used to heat and cool buildings. The thermal performance of GSHP systems strongly depends on the operation ground temperature and thermal quality of the building envelope (TQBE). The operation ground temperature is a function of mean annual air temperature and annual thermal load of the building. The thermal load depends on the TQBE and outside temperature. Given that ongoing global climate change (GCC) affects air temperatures, it also affects the performance of GSHP systems. The magnitude of this impact on a given GSHP system strongly depends on local weather conditions and the TQBE.

The overall aim of the current study is to investigate the impact of GCC on the performance of GSHP systems in different climate. To achieve this aim, three cities located in three climate categories were considered: Stockholm, Sweden (cold), Istanbul, Turkey (mild), and Doha, Qatar (hot). In each city, two buildings were modeled. One was built according to current local building regulations, while the other was built to have a TQBE lower than the standard TQBE. Simulations were run for present (2014) and future (projected for 2050) outdoor designing conditions.

1. Introduction

Human activities based on burning fossil fuels are the cause of ongoing global climate change (GCC) [1–5]. Greenhouse gas (GHG) concentrations in the atmosphere will continue to increase unless global fossil fuel consumption decreases considerably. There is a high level of uncertainty in predictions of future air temperatures, and many scenarios have been developed to project changes in global average temperature under different GHG emission scenarios (e.g., Fig. 1).

The warming rate is not uniform throughout the world. Regional manifestations of GCC vary substantially, with stronger warming expected at higher latitudes and over land areas (Fig. 2).

Consequently, reducing fossil energy consumption has become an urgent issue. As of 2010, heating ventilation and air conditioning (HVAC) systems in buildings accounted for 33% of global GHG emissions [8]. The ever-growing demand for better thermal comfort in winter and summer means that energy consumption in buildings is projected to be higher in the future [9].

In addition to the indoor set temperature, the thermal load (heating and cooling) of a building strongly depends on outdoor design conditions [10]. Several studies have reported a change in energy consumption of HVAC systems as a result of increasing outdoor temperature [9,11–14]. Another important factor in determining the thermal load of a building is the thermal quality of the building envelope (TQBE). The TQBE mainly depends on: (1) the insulation level of the exterior wall, ceiling, and floor; (2) the thermal properties of windows; (3) the air tightness of the envelope; (4) the color of the external shell; and (5) the thermal mass of the external shell. Several publications have documented the impact of improving the TQBE on the thermal load of buildings [15–23].

Although building regulations are moving towards reducing the thermal loads of buildings, the energy use of HVAC systems worldwide is still higher than current building regulations [14]. For instance, the maximum permitted heating load for new residential buildings in Germany under 1995 regulations was 65–100 kWh/m^2/year, but the actual average heating load of existing buildings

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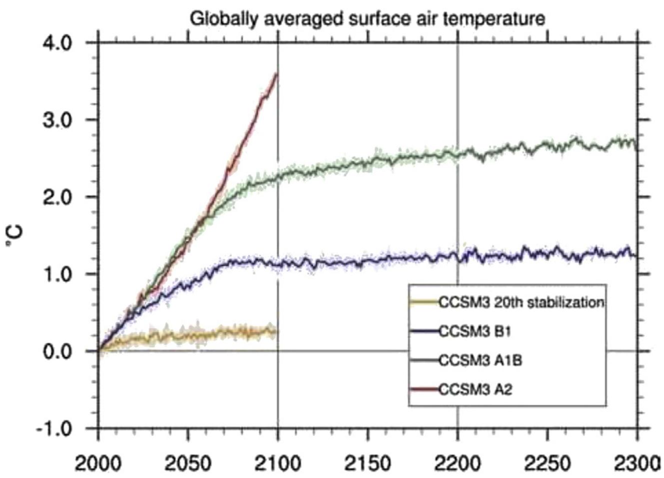

Fig. 1. Time series of globally averaged surface air, from [6].

(most built to a lower TQBE standard) is approximately 220 kWh/m^2/year [24]. The same pattern is evident across Europe. Of the 150 million residential dwellings in the 15 European Union Member States, approximately 72% were built before 1972, to lower TQBE standards than current building regulations [14,17].

The high thermal performance of ground source heat pump (GSHP) systems has made them increasingly common in HVAC systems in commercial, institutional, and residential buildings [25–28]. The performance of GSHP systems depends on the operation ground temperature, which is strongly influenced by the mean annual air temperature and heating to cooling ratio (HCR). It is certain that the mean annual air temperature is increasing because of GCC [5,11,12,15,18–22], while HCR is directly affected by both ongoing GCC and the TQBE. Hence, GCC and the TQBE affect the HCR and operation ground temperature and, consequently the performance of GSHP systems.

Two studies conducted by the author showed the impact of GCC on GSHP system energy use [11,12]. For a given TQBE and GSHP system, the impact of GCC on energy use strongly depends on climate [11]. Under the climate conditions of Vienna, simulations showed a strong relationship between the effect of GCC on the GSHP system and the TQBE [12]. The results above were based on the assumption that the TQBE was the same among buildings [10], and the climate conditions were fixed [12]. However, the consumption of energy for heating and cooling varies with local weather conditions and the TQBE. In another word, based on the climate conditions and the TQBE the reduction in heating energy use might outweigh the increase in cooling energy use, or vice versa. For more details about the relationship between thermal load of a building and the TQBE, see Refs. [12,15–22,24,29].

The overall objective of the present study is to determine how GCC affects the heating and cooling load, and energy consumption of GSHP systems of residential buildings. In addition, the reduction in energy consumption was quantified after improving the TQBE.

2. Description of the GSHP system

A GSHP system moves heat from the ground to buildings in the winter, and moves heat from buildings to the ground in the summer. This heat transfer process is achieved by circulating a heat carrier (water or a water–antifreeze mixture) between a ground heat exchanger (GHE) and heat pump. A GHE typically consists of plastic pipes installed vertically or horizontally under the ground surface. At the beginning of 2010, the installed GSHP capacity in the world was 50,583 MW, producing 121,696 GWh/year [30]. In the USA, GSHP systems are promoted as an important measure to reduce GHG emissions [31].

The temperature difference between the ground and the conditioned space is termed the temperature lift. This temperature plays a major role in determining the coefficient of performance (COP) of GSHP systems (COP = energy delivered/energy consumed). A smaller temperature lift results in a higher COP and consequently, lower energy consumption. Specifically, extracting heat from warmer ground during the heating season and injecting heat into colder ground during the cooling season leads to a better COP.

In the current study, an Engineering Equation Solver model was built to simulate the COP of GSHP systems. The following assumptions were made:

- The refrigerant is R134a;
- The difference between the temperature of the fluid extracted from the borehole and the condensing (for cooling) or the evaporating (for heating) temperature is 10 °C;
- In heating mode, the condensing temperature is 50 °C;
- In cooling mode, the evaporating temperature is 0 °C;
- The pressure drops in the condenser and evaporator are 15 and 25 kPa, respectively;
- The mechanical and isotropic efficiencies of the compressor are 90% and 84%, respectively; and
- The energy consumption of the evaporator (cooling mode) and the condenser fan (heating mode) is 20% of the energy consumption of the compressor.

To verify the model, an experimental study was carried out at Qatar University on a THIBAR22C heat pump unit [32]. For more details, readers are referred to Section 2 in Ref. [33]. Fig. 3 shows the COP of the GSHP system working as a cooling and heating machine along with mean fluid temperature (the mean fluid temperature is the average temperature of the inlet and outlet of the GHE).

3. Methodology

Two buildings were modeled in one city from each of three climate regions: Stockholm, Sweden (cold), Istanbul, Turkey (mild), and Doha, Qatar (hot). Local building regulations differ among the

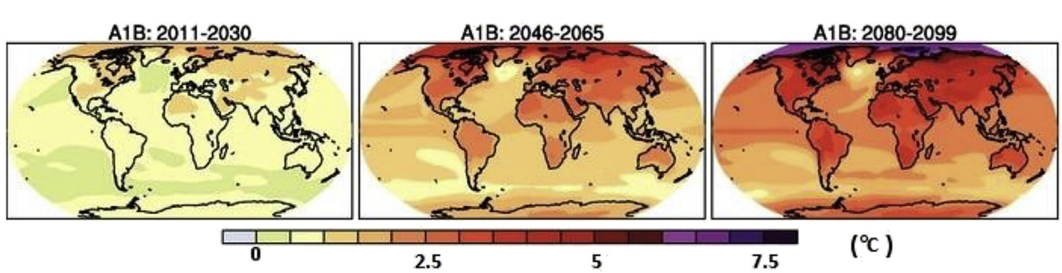

Fig. 2. Projected changes in global average temperatures for three periods. Changes in temperatures are relative to the 1961–1990 average, from Ref. [7].