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Impact of global warming on performance of ground source heat pumps in US climate zones

Pengyuan Shen [a,*], Jennifer R. Lukes [b]

[a] *Department of Architecture, School of Design, University of Pennsylvania, Philadelphia, PA 19104, United States*
[b] *Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, United States*

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ABSTRACT

Ground source heat pumps (GSHP) have attracted increasing attention because of their high energy efficiencies. The aim of this paper is to study the performance of (GSHP) in future climate conditions (2040–2069) by using projected future hourly weather data of selected representative cities in the US to estimate future ground temperature change. The projected hourly weather data and estimated ground temperatures are input to an hourly simulation tool (TRNSYS and eQuest for this research), which provides reliable coupling of GSHP system and building performance.

The simulation results show that global warming will decrease the energy efficiency of GSHP in US residential buildings because a rise in inlet and outlet water temperature is predicted for GSHP systems during the cooling season and because buildings will become more cooling dominated in the future. For office buildings, although the cooling performance of GSHP will not drop significantly under future climate, the overall energy efficiency for the system will decrease due to the increasing energy consumption of the ground loop pump. In the future, considering the significant ground heat imbalance for GSHP operation, GSHP will become less competitive both economically and technically than it is now in the context of US climate zones.

1. Introduction

There has been growing concern about global warming (GW) over the last few decades, especially under the circumstance that the increasing trend in greenhouse gas (GHG) emissions into the atmosphere continues on unabated. The level of GHG in different scenarios projected by the Intergovernmental Panel on Climate Change (IPCC) demonstrates a dramatic rise in the future [1]. In the recently published IPCC Fifth Assessment Report (AR5), there are updated facts and common grounds reached for global climate change [2], showing that In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years and human influence on the climate system is clear.

In the US, commercial and residential buildings consume about 40% of the primary energy [3]. In addition, commercial and residential buildings account for 15.3% of global GHG emissions, including 9.9% for commercial buildings and 5.4% for residential [4], and space cooling and heating is among one of the most important contributors to building energy consumption.

In recent years, different types of renewable energies have been investigated to combat the rise in GHG level and the trend of GW. Ground source heat pumps (GSHP) are one such option because of their high energy efficiencies [5]. When there is a large variation between inside and outside temperatures, as is the case for air source heat pumps, more work is required to provide the same degree of heating or cooling, which reduces the coefficient of performance (COP) [6]. The ground temperature remains nearer to the desired temperature inside a building, hence GSHP is more energy efficient compared with air source heat pump. Generally, a GSHP system with vertical ground heat exchangers is able to extract deep geothermal energy for building heating and cooling because the soil temperature deep underground remains comparatively stable regardless of seasonal oscillation. As indicated by annual energy review of the Energy Information Administration, in 2006 geothermal electricity generation in the US represented a mere 0.5% of the total US energy mix [7]. The United States Geological Survey (USGS) has estimated about 9000 MW of power generation potential from identified geothermal systems and a further 30,000 MW from unidentified sources [8].

However, a question is posed regarding the performance of GSHP in light of global climate change: will GSHP perform as efficiently in the future as it does in the present day, under the current

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* Corresponding author.
E-mail address: penshen@design.upenn.edu (P. Shen).

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Nomenclature

A_s	amplitude of the soil surface temperature variation (°C)
D	dampening depth (m)
ΔT_a	annual mean air temperature change caused by GW compared with that with no GW impacts (°C)
∇T	geothermal gradient (°C/m)
F_b	fraction of evaporation rate for bare soil
h_s	convective heat transfer coefficient at the soil surface (W/m^2 °C)
m	mass flow rate (kg/s)
u	annual mean wind velocity (m/s)
ΔR	Radiation constant (W/m^2)
S_m	annual mean solar radiation (W/ m^2)
k_s	soil thermal conductivity (W/m °C)
T_{va}	amplitude of the air temperature (°C)
Q	space cooling or heating load (W)
S_v	amplitude of the solar radiation (W/m^2)
t_{0a}	phase constant of the air (s)
t_0	phase constant of the soil surface (s)
T_{GST}	ground surface temperature (°C)
T_{ma}	annual mean air temperature (°C)
$T_{z,t}$	temperature at depth ‘z’ and day ‘t’ (°C)
$T_{\mathrm{DGT}}(z,t)$	deep underground temperature at depth ‘z’ meter and year ‘t’ (°C)

Greek letters

α_s	soil thermal diffusivity, second basis (m^2/s)
α_s'	soil thermal diffusivity, day basis (m^2/d)
α_s''	soil thermal diffusivity, year basis (m^2/y)
β	absorption coefficient
ε	hemispherical emittance of ground surface
φ_I	phase angle between the insolation and the air temperature (rad)

w	annual angular frequency (rad/s)

Subscripts

a	air
com	compressor
in	inlet
out	outlet
s	soil

Acronyms

COP	coefficient of performance
DGT	deep ground temperature
EED	Earth Energy Designer
IPCC	Intergovernmental Panel on Climate Change
GCM	global climate model
GHB	ground heat balance
GHG	greenhouse gas
GLHE	ground loop heat exchanger
GSHP	ground source heat pump
GST	ground surface temperature
GW	global warming
HVAC	heating, ventilation, and air-conditioning
RH	relative humidity
SAT	surface air temperature
SPARK	simulation problem analysis and research kernel
SRES	special report: emissions scenarios
SSGT	sub-surface ground temperature
TMY	typical meteorological year
UGT	undisturbed ground temperature
USGS	United States Geological Survey

climate condition and building heating/cooling demand? Regardless of GW, the ground surface temperature (GST) undergoes changes because soil temperatures at shallow depths are subject to considerable variation on both daily and annual bases [9]. In general, the ground temperature change is a direct consequence of a change in surface air temperature (SAT) [10]. In addition, records show that SAT has increased 1.4 °C from 1880 to 2008 [11]. This indicates that longer time frame temperature variations due to GW should be taken into consideration. Although the change in GST and sub-surface ground temperature (SSGT) are unlikely to exert significant influence on deep ground temperature (DGT), it can still exert impact on the thermal performance of the vertical ground heat exchangers of the GSHP. Furthermore, when it comes to the influence of GW on building energy use patterns (as building heating and cooling energy use depend greatly on ambient air temperature and relative humidity), one cannot discount the possibility that GW perturbs GSHP performance. Thus, changes in prevailing climate conditions will have potential impact on the overall performance of GSHP.

Little research into the impacts of GW on GSHP performance has been conducted. In recent work by Kharseh et al. [12], the impact of GW on the future performance of GSHP in a small residential house is assessed under the climate conditions of three selected cities in Sweden, Syria and Saudi Arabia. However, the research results are rough estimation on studying the impacts of GW on GSHP performance. The results of this important and novel work show that GW reduces the energy demand used to run the heat pump in a cold climate and increases it in a hot climate. However, the research does not include representative baseline climate data like TMY2 or TMY3 and support from a sound global climate model (GCM) outcome when predicting future building heating and cooling. The adopted method only estimates future building heating and cooling demand pattern by using a simple prediction method on heating and cooling degree hour. Moreover, the different air temperature amplitudes and other important factors influencing ground temperature change, including solar irradiation and wind speed, are not taken into account. Additionally, large-sized GSHP systems are not analyzed. A more detailed and reliable building energy performance simulation and site specific hourly weather data are imperative in studying the impact of GW on the performance of GSHP.

The objective of this research is to study the impact of GW on the performance of GSHP by using hourly downscaled climate data, not only taking into account air temperature changes and building energy load differences in the future, but also assessing changes in sub-surface and deep underground temperatures. By establishing and simulating a typical GSHP system model in TRNSYS for residential and office building models in eQuest based on hourly morphed future weather data, the future performance of GSHP can be predicted and analyzed.

2. Hourly weather data downscaling

2.1. Climate model

One of the most well-known GCM, HadCM3 [13], is adopted to generate the future weather file in this paper. HadCM3, like other GCMs, is a grid point model with large grid cells (2.5° in latitude and 3.75° in longitude over land areas). In this paper, the A1FI