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Technical and economic feasibility of unitary, horizontal ground-loop geothermal heat pumps for space conditioning in selected california climate zones

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ABSTRACT

This work investigates the viability of unitary 3.5 kW_t, ground-source terminal heat pumps (GTHP) employing horizontally drilled geothermal heat exchangers (GHX) relative to air-source packaged terminal heat pumps (PTHP) in hotels and motels and residential apartment buildings in California's coastal and inland climates. The GTHP can reduce hourly peak demand for the utility by 7–34% compared to PTHP, depending on the climate and building type. The annual energy savings of up to 5% are highly dependent on the water-pump energy consumption relative to savings associated with the ground-air temperature difference (ΔT). In mild climates with small ΔT, the pump energy use may overcome savings from utilizing a GHX. The levelized cost savings, ranging from \$1.7/yr-m^2 to \$3.6/yr-m^2, were mainly due to reduced maintenance and lifetime capital costs. Without these reductions, the GTHP does not appear to offer significant advantages over PTHP in the climates studied. The GTHP levelized cost was most sensitive to variation in installed cost and system efficiency. These results can inform installers and decision makers about the viability of this technology, which is highly dependent on climate and building type.

1. Introduction

Energy efficiency in buildings is crucial towards achieving reductions in cost and greenhouse gas emissions [1]. Depending on the building design, occupancy type, equipment controls, and climate conditions, heating, ventilation and air conditioning (HVAC) equipment typically represent 1/3 of a building's energy demand. Based on best available data, HVAC energy use in the lodging (hotels and motels) building sector in California accounts for approximately 38% of total building electrical energy end-use and 17% of total building natural gas end-use [2]. HVAC energy use in the multifamily (apartments) building sector accounts for approximately 27% of total building electricity and natural gas use [3]. Measures targeted at reducing HVAC energy use can therefore significantly reduce the total energy use of a building.

Relative to air-source heat pump systems whose performance degrades during extreme ambient temperatures, geothermal heat pumps (GHP) maintain operating performance because they exchange heat with the ground through a ground-loop heat exchanger (GHX). The ground (i.e. soil) experiences smaller temperature variations over the year, particularly at increasing depth. Based on case studies of actual installations and modeling efforts [4–9], GHPs have been shown to provide energy savings (site basis) ranging from 30% to 62% when compared to various air-source systems (typically utilizing gas heating). Energy cost savings is augmented by maintenance-cost and lifetime-capital-cost reductions, resulting in total cost savings ranging from 34 to 42%. Levelized capital cost reductions are due to the longer projected GHP lifetime, typically 20–25 years, compared to 15–20 years for air-source units. Additionally, the GHX is rated for 50 years of service [10,11]. Maintenance cost savings are attributed to protection from exposure to exterior weather conditions (sun, snow, dust, rain, etc.)

Despite the energy, maintenance and long-term operational benefits, GHPs incur high capital costs, which have limited their adoption in the United States. As of 2011, GHPs accounted for only 2.2% of the value of all shipments of HVAC equipment while air source heat pumps accounted for over 10% [4]. In the residential and commercial sectors, the main market barriers for the technology are attributed to the GHX design complexities and limited experience among installers [12,13]. Complexities in design arise

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Nomenclature

CES	Carbon emissions from energy use, kg CO_2/Wh_t
CEUS	California Commercial End-Use Survey
CL	Cooling load, kW_t (kW thermal)
Co	Cost at the 1st year of analysis, $
COP	Coefficient of performance
DEER	Database for Energy Efficient Resources
EC	Total energy consumption, kWh_e (kWh electricity)
EEI	Emissions index for electricity, kg CO2/kWh_e
EF	Efficiency factor, representing annual COP degradation
EU	Electricity use of the PTHP and GTHP, kWh_e
EUS	Energy use of thermal service, kWh_e/Wh_t
GC	Total natural gas consumption, kWh_t
GEI	Emissions index for natural gas, kg CO_2/kWh_t
GHP	Ground-source heat pump
GHX(s)	Geothermal heat exchanger(s)
GTHP(s)	Unitary ground source terminal heat pump(s)
H_b	Facility height, m
HD	Horizontally drilled
HDPE	High density polyethylene
HL	Heating load, kW_t
HVAC	Heating, ventilation and air conditioning
L	GHX bore length, m
L_b	Facility length, m
LCOS	Levelized cost of service, $/$Wh_t$
M	Total number of analysis year, 20 yr
P	Present cost, $
PTHP(s)	Packaged terminal heat pump(s)
Q	Heat transfer, kW_t
T_{ew}	Entering water temperature to heat pump, °C
T_g	Ground temperature, °C
T_m	Mean GHX bore temperature, °C
T_{oa}	Outside air temperature, °C
TOU	Time of use
$\dot{W}$	Power, kW_e
W_b	Facility width, m
W_{b1}	Width of individual lodging building, m
W_{b2}	Separation distance between individual lodging building, m
c	Subscript, cooling
e	Subscript, electric
h	Subscript, heating
i	Subscript, hourly index
j	Subscript, yearly index
k	Thermal conductivity, W/m-K
n	Interest rate, %
s	Escalation rate, %
t	Subscript, thermal
y	Subscript, index for each component of costs

from variability in ground conditions such as non-uniform conductivity which directly influences heat exchange performance, from the presence of existing below grade infrastructure such as utility lines (typically buried at 1 m depth in California), and from regulatory limitations on boring primarily due to concerns on potential contamination of ground water. These factors manifests in longer installation times and increased costs.

This study was motivated by the drive to develop a lower cost GHP system. As a subgroup of GHPs, ground source terminal heat pumps (GTHPs) are self-contained terminal units coupled to a U-tube, horizontally drilled (HD) ground loop through an exterior wall in order to deliver space cooling/heating service without the use of an interior ducting system. HD GHX have the lowest installed cost compared to other closed loop GHX, such as vertical bores that require large and expensive specialized drilling equipment that are often hindered by site obstructions and add to logistic costs, or horizontal trenches that require extensive and time-consuming excavation. The HD GHX discussed here utilizes a compact directional driller, which is not hindered by the above issues.

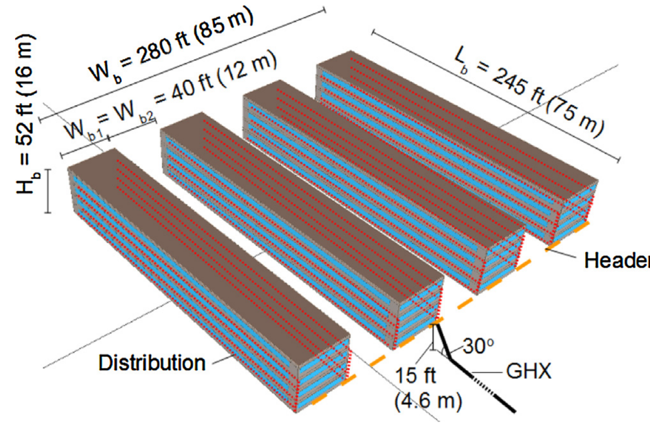

Fig. 1. Schematic of the modeled lodging facility consisting of four 4-story buildings. Fine dotted lines represent distribution piping running along the outside of the building. Dashed lines represent the header connected to multiple GHX bores. A single HD GHX bore is shown as an example.

In California, GTHP appears to have applicability in low-rise lodging and multifamily facilities, whose total floor areas were estimated at 620,000 m^2 and 3,700,000 m^2 respectively in the inland climate, and 260,000 m^2 and 9,200,000 m^2 respectively in the coastal climate [2,3]. These two climates are based on the California Energy Commission building climate zone classification [14]. The former, represented by the city of Oakland, California, is characterized by a mild outside air temperature (T_{oa}) profile, while the latter, represented by the city of Fresno, California, is characterized by more extreme annual temperature swings. At present, application of this system in these building sectors in California has been very limited.

Through modeling and sensitivity analysis, this paper investigates the potential benefits of the GTHP within the low-rise lodging and multifamily facilities when compared against unitary air-source packaged terminal heat pump (PTHP) systems in California's coastal and inland climates.

2. Description

The major components of a GHP system include the heat pump unit, the air delivery system and the hydronic system, which comprises of the GHX and distribution piping. The arrangement of these components within a building can vary widely. In the case of the GTHP, the air delivery system is self-contained within the heat pump unit, which is typically installed through an exterior wall for connection with the GHX. The GHX consists of multiple horizontally bored U-tube high-density polyethylene (HDPE) pipe surrounded by grout. The bore enters the ground at 30° and levels out at the typical design burial depth of 4.6 m after traveling 7.9 m horizontally (Fig. 1). Since a typical bore length is 76 m long, the bore is exposed primarily to the ground temperature at the burial depth.

At depths shallower than 16 m, the temperature of the ground (T_g) can vary from one season to the next depending on the soil type and climate [15]. At a depth of 4.6 m in the California inland and coastal climates, T_g can vary by 8 °C and 3 °C, respectively. During cooling period, T_g is higher than it would be during heating period. This temperature swing reduces the performance (efficiency and