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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

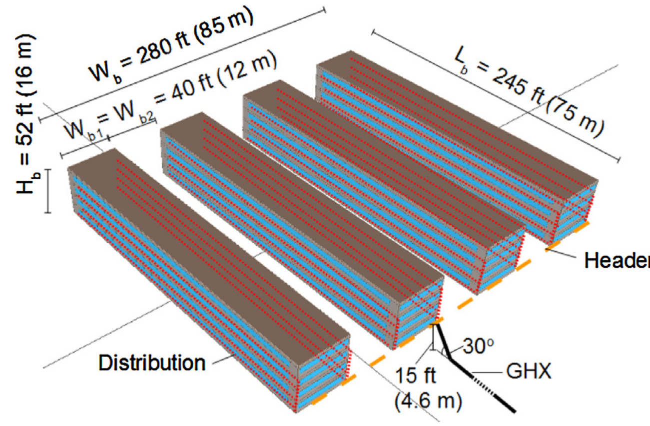

Fig. 1. Schematic of the modeled lodging facility consisting of four 4-story buildings. Fine dotted lines represent distribution piping running along the outside of the building. Dashed lines represent the header connected to multiple GHX bores. A single HD GHX bore is shown as an example.

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.

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 capacity) of the GTHP as it would have to operate at a higher condensing temperature during cooling mode and lower evaporating temperature during heating mode relative to the fairly constant undisturbed T_g of deeper soil.

One factor influencing the performance of any GHP is the temperature of water entering the heat pump (T_{ew}). T_{ew} is influenced by the heat transfer performance of the GHX, which is based on the temperature differences between the bore and the ground and the thermal conductivities of the borehole and soil. Analytical approaches for designing a GHX has been proposed by Bernier [16,17] and IGSHPA [15]. Based on the works of Hellstorm [18], Carslaw and Jaeger [19] and Ingersoll and Plass [20], Bernier's method accounts for long-term thermal imbalances via three thermal pulses (annual, monthly and hourly) and borehole thermal interference due to the combination of bore-to-bore spacing and thermal imbalance. Thermal imbalance describes the gradual rise/decrease in ground temperature due to unequal net heat transfer between the GHX and ground. This is an increasingly important consideration with the design of deeper GHXs as heat diffusion to the ground surface is slow relative to shallower GHXs. Bore interference describes a similar rise/decrease in ground temperature due to proximity of bores. On the other hand, IGSHPA's method for horizontal-bored GHX was based on the line-source theory plus a number of simplifying assumptions that provide satisfactory solutions for small pipes within a narrow range of a few hours to months [21]. IGSHPA has also suggested correction factors based on the space load profiles in order to account for long-term thermal imbalance.

Bernier's methodology seems applicable for horizontal GHX provided that IGSHPA's suggested correction factors are applied. The calculated bore lengths from the modified Bernier approach (A) were compared to the results from the unmodified Bernier (B) and IGSHPA (C) methodologies. Method C resulted in the shortest U-tube GHX design, followed by A and B. ASHRAE's tabulated recommended lengths for horizontal 2-pipe GHX [22] were much closer to the results of A than either B or C, thus providing a measure of validation. Relative to C, the benefit of a larger GHX obtained from A is higher heat pump efficiencies as T_{ew} will approach T_g more closely than T_{ew} of a smaller GHX, but this can significantly increase capital costs.

An efficient hydronic system is crucial for any GHP system to achieve energy savings over air-source systems. A balance between efficiency and implementation cost is typically struck when the hydronic system's power draw per system cooling capacity is designed within a range of 14 W/kW$_t$ to 22 W/kW$_t$, given a design flow per cooling capacity of 0.19 m^3/hr-kW$_t$ [23].

The levelized cost is an economic metric used by agencies such as the Energy Information Administration and the US Department of Energy's National Renewable Energy Laboratory to compare technologies that provide the same service. Generally, the metric represents the total capital, fuel and maintenance costs of a system over a defined service life, normalized by the desired output of the system (i.e. cost per electricity generated, $/kWh). Financing costs and the effect of inflation and discount rates are also factored in. In this work, the levelized cost describes the total system installation and operation costs per unit heating and cooling energy over the analysis period and represents the cost of service equivalent to a net present value of 0.

3. Methodology

The methodology of the present study is summarized as follows: 1) definition of building load profiles and dimensions, 2) development of system performance data, 3) sizing and modeling of the baseline and alternate systems, and 4) economic evaluation.

Table 1
Summary of loads and facility area.

Item	Climate	
	Coastal	Inland
Multifamily		
Floor Area, m^2	1200	1200
Peak Heat Load, kW$_t$	44	59
Peak Cool Load, kW$_t$	48	85
Annual Heat Load, MWh$_t$	41	31
Annual Cool Load, MWh$_t$	6	89
Lodging		
Floor Area, m^2	14,500	14,500
Peak Heat Load, kW$_t$	144	261
Peak Cool Load, kW$_t$	490	891
Annual Heat Load, MWh$_t$	274	249
Annual Cool Load, MWh$_t$	896	1540

3.1. Building load profiles and schematic

The lodging and multifamily building models in the present study are based on those used in a previous study by Pacific Gas & Electric (PG&E) since they are representative of consumers in their service area [24]. The design of the GTHP system depends on the space heating and cooling load profiles of each of these buildings. These profiles were developed using California Commercial End-Use Survey (CEUS) lodging data and the Database for Energy Efficient Resources (DEER) prototype multifamily data [25], respectively (Figs. 3–6 and Table 1). The profiles are driven not only by the occupancy type but also the ambient weather conditions. The coastal climate is characterized by a mild outside air temperature (T_{oa}) with an annual mean, maximum and minimum of 14 °C, 33 °C and 2 °C, respectively. By contrast, the inland climate is more extreme with an annual mean, maximum and minimum T_{oa} of 18 °C, 42 °C and −2 °C, respectively. Peak hourly cooling and heating loads are both higher in the inland climate.

The physical schematic of the modeled buildings directly influences the arrangement of GHX distribution piping network and pumping energy use. The dimensions for the modeled lodging facility were estimated based on total floor area of a typical low-density lodging facility in California (Fig. 1). This is in contrast to a high-density lodging facility, which would typically be represented by single high-rise building. H_b, W_b and L_b represent the facility height, width and length, respectively. W_{b1} and W_{b2} represent individual building width and the separation distance between buildings. The dimensions of the modeled multifamily building were extracted directly from DEER (Fig. 2). The lengths of the distribution and header piping which influence the pump energy use are based on the facility dimensions.

The building energy consumption, EC, over the 20-year analysis period was calculated by Eq. (1):

$$EC = \sum_{j=1}^{20} \left(\sum_{i=1}^{8760} \left(\left(\frac{\left(\frac{CL_i}{COP_{c,i}} + \frac{HL_i}{COP_{h,i}} \right)_j}{(1 - EF_j)} \right) + \mathrm{EC}_{misc,\,i,\,j} \right) \right) \tag{1}$$

where i and j are hourly and yearly indices, respectively; CL and HL are cooling and heating loads in absolute value; COP is based on T_{oa} and T_{ew}; EF is an annual COP degradation of 1.1% due to wear and tear [26] which are accounted for at each year except at the 1st and replacement year (16th year for the PTHP); and EC_{misc} are the non-HVAC loads. Based on historical trends of the California Title 24 building energy code which specified minimum equipment efficiencies and best practices for energy efficiency in the state [27,28], a 7% rise in COP every 12 years was considered in the model. This efficiency gain replaces EF at the replacement year, as applicable.

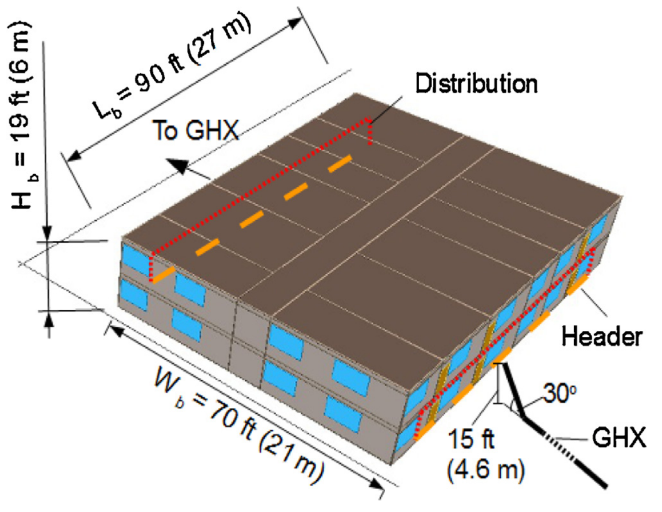

Fig. 2. Schematic of the modeled 2-story multifamily apartment. Fine dotted lines represent distribution piping. Dashed lines represent the header. The GHX bores are connected to the two headers on the sides of the building.

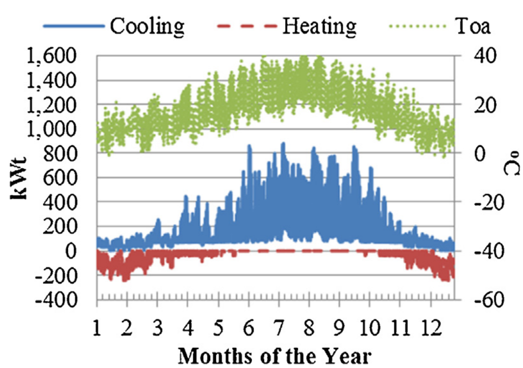

Fig. 3. Lodging load profile in Inland climate.

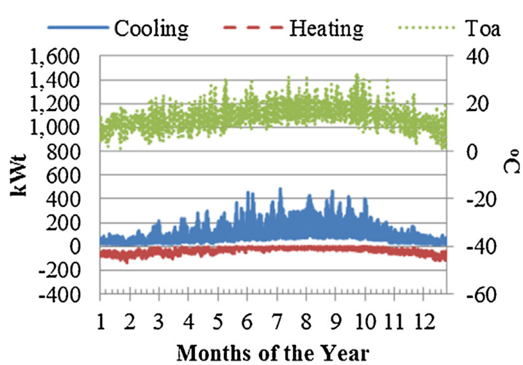

Fig. 4. Lodging load profile in Coastal climate.

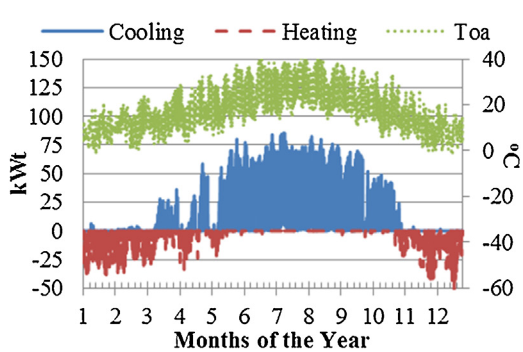

Fig. 5. Multifamily load profile in Inland climate .

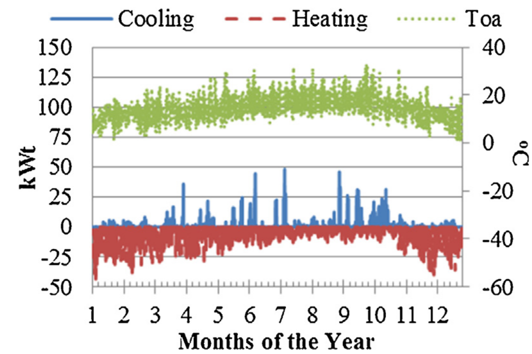

Fig. 6. Multifamily load profile in Coastal Climate .

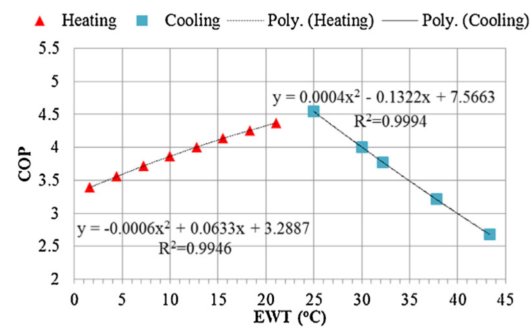

Fig. 7. GTHP COP as a function of T_{ew}.

3.2. Heat pump coefficient of performance

A relationship between COPs in heating and cooling and T_{ew} were developed empirically for the GTHP based on 15-min data sampling of two units operated at a test site at the Domes cooperative housing community at the University of California, Davis. The raw data compiles as a scatter plot across a T_{ew} range from a period of Feb 2014 to Jan 2015, and has been condensed with selected T_{ew} for simplicity. Manufacturer data for two brands of comparable commercial water-source heat pumps [29,30] were combined with the test data to generate the COP curves used in this study (Fig. 7). The GTHP cooling (heating) COP was higher (lower) than the two commercial systems, but all three followed similar trends. In this case, the COP is defined as the ratio of the cooling or heating capacity over the sum of the compressor power, control systems power draw – and the pumping power needed to overcome the pressure drop only in the water-refrigerant heat exchanger. Pump power calculations for the distribution lines, headers and GHX are evaluated separately based on the piping scheme of the modeled buildings.

The COP trends for the baseline system was similarly developed using data from a PTHP currently operated at the pilot site in conjunction with two brands of comparable commercial air-source heat pumps [31,32]. For the same condensing/evaporating temperatures, the COP of the test unit was practically the same as the two commercial units.

3.3. GHX design

The design of the horizontal GHX in this study is based on the analytical approach presented by Bernier [16,17] with slight modification according to IGSHPA [15]. The following IGSHPA correction factors for 6-m bore-to-bore separation were used: 1.16 for inland lodging, 1.17 for coastal lodging, 1.1 for inland multifamily, 1.16 for coastal multifamily. A wet shale ground type with thermal conductivity, k = 1.9 W/m-K was assumed for both climates based on the

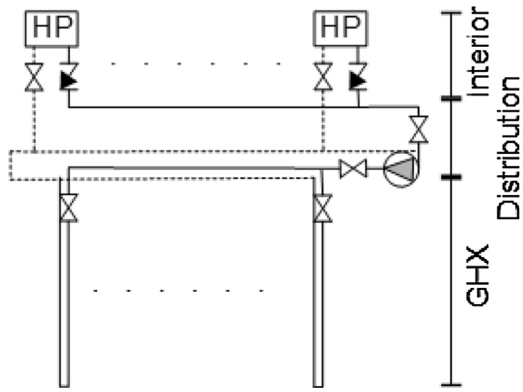

Fig. 8. Central pumping schematic.

median value provided by Bernier. The GHX bore consists of 2.54-cm diameter HDPE piping with thermally enhanced grout with k = 2.1 W/m-K. A burial depth of 4.6 m and an entry angle of 30° were assumed in the present model (Fig. 1). A GHX design flow of 0.19 m^3/hr-kW_t was used based on recommendations of [23].

The water temperatures entering the heat pump were iteratively estimated based on the far-field assumption where T_g is far enough from the bores to be independent of instantaneous heat transfer, Q, on an hourly time scale. The design COP recommended by [22] was first applied across all hours to estimate the mean GHX bore temperature (T_m). Changes in T_m effect changes in T_{ew}. The COP value based on the revised T_{ew} was then used to recalculate Q. This process was iterated until the COP value converged. The resulting annual T_{ew} approached T_g based on the magnitude of load and somewhat traced the sinusoidal profile of T_g. Estimations of the hourly T_m are based on the modeling assumption that only a fraction of the design bore length is active, based on the required ground heat transfer to satisfy the space load at any particular hour. Thus, pumping energy use is minimized.

3.4. Pumping system

A closed-loop central and sub-central circulation system were specified for the lodging and multifamily facilities, respectively. In the central system (Fig. 8), each heat pump was connected to a single bore field via a main header and variable speed pump. In the sub-central system (Fig. 9), equal numbers of GTHPs were connected to each of the two bores. Additionally, each heat pump was served by a dedicated, single-speed pump. In both systems, a

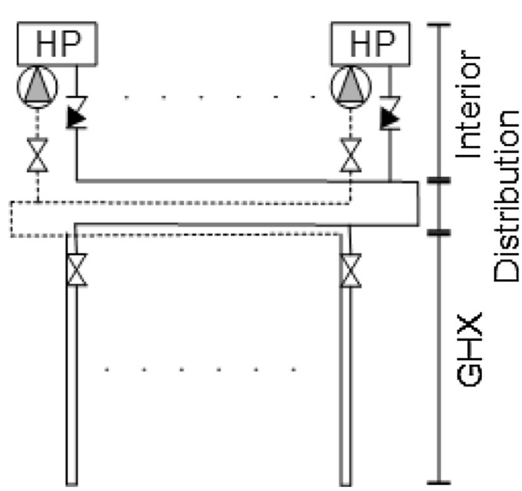

Fig. 9. Sub-central pumping schematic (multifamily).

valve was specified at the supply line of each U-tube bore which closes at part loads in order to minimize pumping demand. The pipe diameters for the header and distribution lines, and the number of parallel GHX bores were adjusted to meet the 14 W/kW_t and 22 W/kW_t benchmarks recommended by Kavanaugh, Rafferty [23] for the lodging and multifamily facilities, respectively.

3.5. Cost and emissions calculations

3.5. Cost and emissions calculations

The levelized cost of service, LCOS, (\$/Wh_t) represents the dollar value to supply each unit of thermal load to produce a net present value of zero, and was calculated using eqn. (2) and (3).

$$LCOS = \left(\frac{\sum_y ((P_y) \left(n(1+n)^M\right)}{\left((1+n)^M - 1\right) \left(\sum_{j=1}^{20} \sum_{i=1}^{8760} (CL_i + HL_i)_j\right)} \right) \quad (2)$$

$$P_y = \sum_{j=1}^{20} Co_y \left(\frac{(1+s_y)}{(1+n)} \right)^j \quad (3)$$

where P is the net present value of all costs of the GTHP and PTHP systems over their lifetime, expressed in dollars; Co is the cost at the 1st year of analysis; n and s are the annual interest of 3% [33] and annual price escalation rates (2% for capital cost[34], and between 0.4% and 5.7% for the various components of energy based on the utility historical 2003–2014 trends [35]), respectively; M is 20 years; the y subscript denotes the various components of total cost; and j is the analysis year (1–20). Capital cost, including the PTHP, GTHP, HDPE piping and insulation, pumps, variable speed drive controller and GHX drilling and grouting, was evaluated at j = 1 for the PTHP and GTHP, and at the replacement year j = 16 for the PTHP. Since the baseline system was retired early at the 20th year of analysis (5th year of service for the replacement unit installed at year 16), salvage value was taken as the book value calculation from the U.S Federal General Depreciation System (MACRS) depreciation[36]. Only the GTHP and pumps are considered at replacement of the GTHP system. Published cost data [37] and contractor pricing were used to establish capital costs. Based on [38,39], annual maintenance costs for an air-source heat pump were \$3.55/m^2 in 1985 and \$2.99/m^2 in 1999. For a ground-source heat pump, these costs were \$1.39/m^2 in 1999 and \$1.18/m^2 in 2006. A reduction in maintenance cost (as opposed to escalation based on inflation) was reported for both systems. To project these costs to the years of analysis, exponential curve fits based on the aforementioned data has been assumed.

Total facility energy cost was calculated from the time-of-use utility rate schedules for low-density residential (coded as E-7 and G-1) and medium density commercial facilities (coded as A10S and GNR-1) [35]. In the time-of-use rate scheme for the lodging facility, electrical energy use and demand in the summer (May-Oct) is divided into 3 periods: peak (highest cost), part-peak, and off-peak (lowest cost). Peak period occurs between 12:00–18:00, off peak between 21:30–08:30 and part-peak the remaining hours of the day. Electrical energy use for lodging in the winter (Nov-Apr) is divided into 2 periods: part-peak (08:30–21:30) and off-peak. For the multifamily facility, both the summer and winter-time use is divided into 2 periods: peak (12:00–18:00) and off-peak (remaining hours of the day). Each facility has a specific summer and winter natural gas rate. The load-normalized PTHP and GTHP energy use due to thermal service (EUS) and the carbon emissions due to energy use (CES) were calculated using Eqs. (4) and (5), respectively. EUS and CES represent the magnitude of energy use per unit

Table 2
Summary of system configurations.

Component	Lodging		Multifamily	
	Inland	Coastal	Inland	Coastal
1-ton (3.5 kW) PTHP, units	254	254	24	24
1-ton (3.5 kW) GTHP, units	254	254	24	24
GHX 3-cm U-tube bore length, m	24,410	10,254	2053	902
8-cm distribution & header pipe with 3-cm fiberglass insulation, m			176	176
10-cm distribution pipe with 3-cm fiberglass insulation, m	4971	4971		
15-cm header pipe with 3-cm fiberglass insulation, m	171	171		
Central hydronic pump (1 service + 1 backup), kW	(2) 15 kW	(2) 7.5 kW		
Unitary hydronic pump (1 for each GTHP), W			(24) 62 W	(24) 62 W

thermal load served, and the carbon emissions per unit thermal load served, respectively.

$$EUS = \sum_{j=1}^{20} \left(\frac{\mathrm{EU}_j}{(M)\left(\sum_{i=1}^{8760} (\mathrm{CL}_i + \mathrm{HL}_i)_j\right)} \right) \quad (4)$$

$$CES = \sum_{j=1}^{20} \left(\frac{\mathrm{EC}_j(\mathrm{EEI}) + \mathrm{GC}_j(\mathrm{GEI})}{(M)\left(\sum_{i=1}^{8760} (\mathrm{CL}_i + \mathrm{HL}_i)_j\right)} \right) \quad (5)$$

where EU is the total annual energy use of the PTHP and GTHP systems, GC is the facility gas consumption, and EEI and GEI are the utility carbon footprint indices for electricity and natural gas, respectively [40].

3.6. Sensitivity analysis

Factors that affected the LCOS of the GTHP include overall system efficiency, capital cost, maintenance cost, equipment life, energy cost rates and interest rate. For each facility in each climate zone, sensitivity of the LCOS was investigated by varying these factors in 10% increments. Sensitivity analysis results for the most significant factors are presented in the next section.

4. Results and discussion

Due to differences in occupancy, thermal load and building dimensions, the lodging facility required significantly more unitary heat pump units, longer distribution piping and GHX, and larger water pumps than the multifamily facility (Table 2). In order to meet pumping power benchmarks, 140 parallel GHX bores were specified for the inland lodging building. For the coastal lodging, and coastal and inland multifamily facilities, the numbers of parallel bores were 70, 7 and 12, respectively. At peak heating and cooling loads, water enters the GHX at 7 °C and 38 °C, respectively, and leaves at 10 °C and 32 °C, respectively. These temperatures vary depending on T_g and the building load, and T_{ew} approaches T_g within 5 °C. The GTHP COP varies from 3.7 to 4.5 depending on T_{ew}. The pumping power requirement is greatest through the GHX and ranges from 50% to 70% of the pump capacity. For the coastal lodging, inland lodging and the two multifamily facilities, the pump energy consumption represents 3%, 6% and 10% of the GTHP system energy consumption, respectively.

The contribution of the GHX to the total system cost increased significantly as cooling load increased. The larger of the space loads in the inland and coastal climates dictated the total number of heat pumps for the facility due to the assumption of identical interior building configuration. The GHX length for the facilities in the coastal climate is approximately 40% the length required in the inland climate because the coastal space cooling loads are smaller and the mean ground temperatures are lower.

Table 3
Summary of energy use and emissions reductions.

Item	Lodging (%)		Multifamily (%)	
	Inland	Coastal	Inland	Coastal
Peak Heating (1st year), %	24%	25%	20%	23%
Peak Cooling (1st year), %	25%	7%	34%	10%
Average (20 years), %	2%	3%	5%	−1%
EUS, kWh_e/Wh_t	5	8	15	−4
CES, kg CO_2/Wh_t	1	2	4	−1

Over the analysis period, energy use reductions ranging from 5% to 2% were found for all cases except for the coastal multifamily facility (Table 3). In the latter case, the pump energy use cancels any savings realized from utilizing a ground loop, which is minimal due to the mild coastal weather. Conversely, large facilities (lodging) situated in more extreme climates (inland) benefit from significantly lower demand at peak loads and lower overall energy use from the use of the GTHP. Larger differences between T_g and T_{oa} during these peak hours resulted in higher demand reductions. In this study, inland (both lodging and multifamily) facilities consistently see energy savings from GTHP. Thus, those inland facilities that do not have the infrastructure to support internally centralized systems (such as a central heat pump) can be targeted for implementation of this technology.

A parallel study compared GTHP against unitary air conditioners with gas heaters as the baseline system [24]. For the lodging facility, the GTHP energy savings were estimated at 48% in the coastal climate and 39% in the inland climate (site energy basis), which correspond to 23% and 25%, respectively on source energy basis, assuming a 33% fuel-to-electricity conversion efficiency for heating energy use. For the multifamily facility, these savings were 72% in the coastal climate, and 47% in the inland climate (site energy basis), which correspond to 36% and 30%, respectively on source energy basis. The differences in the magnitude of savings were attributed to lower efficiency of the combustion-based heating system relative to the heat pump heating COP. Additionally, the baseline unitary air conditioner in the parallel study was modeled with a lower COP in cooling than unitary air-source heat pumps based on the trends provided in Title 24. Thus, relative to the present study, the potential savings were higher, especially in heating dominated climates. The results of the parallel study agreed with the estimates provided by Battocletti and Glassley [4], and highlighted the potential benefit of the GTHP. In applications where existing systems are combustion-based in heating or have lower efficiencies in both heating and cooling, the GTHP appears to be promising from an energy efficiency standpoint.

For lodging, the reductions in LCOS were estimated at 7.7% (\$36/W_{th} or \$2.8/yr-m^2) and 8.7% (\$28/W_{th} or \$3.6/yr-m^2) in the coastal and inland climates, respectively (Fig. 10). For multifamily, the reductions were 5.5% (\$70/W_{th} or \$2.7/yr-m^2) and 3.8% (\$16/W_{th} or \$1.7/yr-m^2) in the coastal and inland climates, respectively (Fig. 11). Using the estimated floor areas of the target market

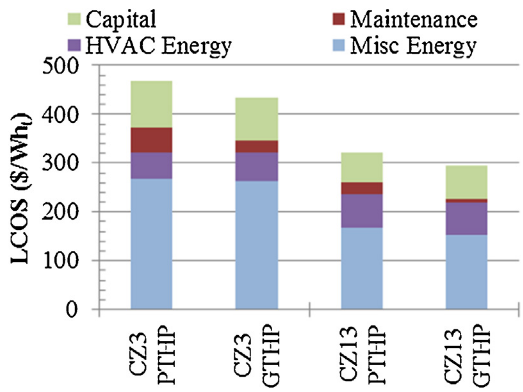

Fig. 10. LCOS for modeled lodging facility.

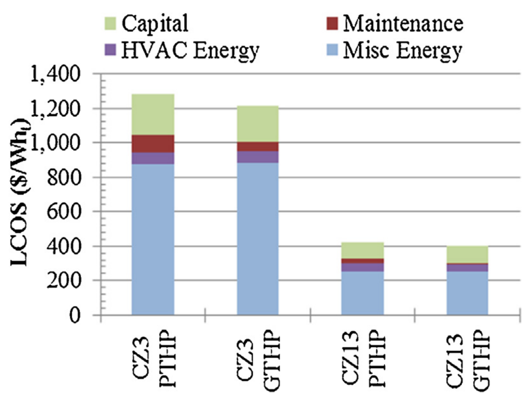

Fig. 11. LCOS for modeled multifamily facility.

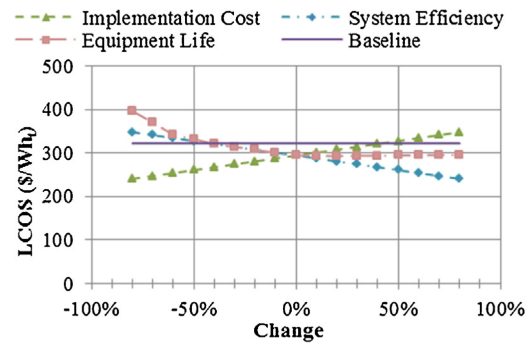

Fig. 12. Inland lodging sensitivity.

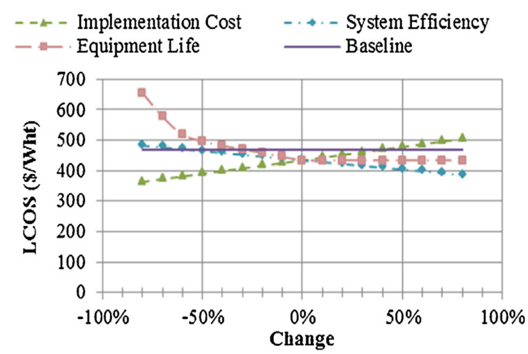

Fig. 13. Coastal lodging sensitivity.

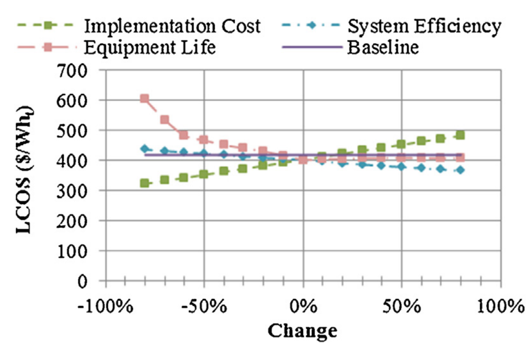

Fig. 14. Inland multifamily sensitivity.

described in Section 1 (facilities served only by electricity), application of the GTHP across the two climate zones has the potential to achieve annual cost savings of approximately $ 100 million.

At all facilities, the major portion of total electrical energy use is attributed to non-HVAC uses. For the lodging facility, 17% and 30% of the total energy use is attributed to the HVAC system in the coastal and inland climate, respectively. For multifamily, the fraction is smaller: 7% and 15% in the coastal and inland climate, respectively. The energy cost reduction between the baseline and alternate cases is greater for larger facilities situated in more extreme climates, even though these facilities required large GHX bore fields, which increased the implementation cost. The majority of levelized cost savings are due to projected lower maintenance requirements and longer operating life of the GTHP. Neither factor was validated with this particular study, but is well-documented for GHP systems in general [10,11,38,39]. A long-term study on maintenance cost and equipment life for the GTHP would give more insights into the total savings potential.

Application of the GTHP in both climates zones can result in cost reductions, but for different reasons. In the coastal climate where loads are smaller than in the inland climate, energy cost savings are negligible or negative but this reduced savings is offset by capital cost reductions. In the inland climate, GTHPs can make more effective use of the heat exchange with the ground for improved system efficiency compared to the GTHPs in coastal climate, but the larger loads result in larger system size, which offsets the capital cost savings due to longevity. Furthermore, the economic viability of GTHP are dependent on electricity price [41]. When an all-electric baseline system is considered, higher electricity rates can improve the cost effectiveness of the GTHP, and vice versa. On the other hand, when a natural gas heating system is considered as the baseline, higher electricity rate reduces the viability of GTHP, and vice versa, especially in heating dominated climates.

To investigate the effect of rate structure on the total cost savings, the LCOS analysis was repeated using non time-of-use (TOU) rate structures. Compared to the results under TOU rates, the LCOS savings under non-TOU rates are lower in the inland climate (5.4% for lodging and 3.2% for multifamily) but higher in the coastal climate (8.1% for lodging and 5.9% for multifamily). Thus, facilities subject to time-of-use rates will further benefit from operating efficiency gains of the GTHP during cooling periods because lower demand occurs during the periods of high utility rates. From the utility point of view, the GTHP can help reduce demand during peak period and mitigate the need to supply more power by building new power plants.

4.1. Sensitivity

Generally, LCOS is most sensitive to changes in implementation cost (Figs. 12–15). Reduction of GTHP installation costs is critical, either by added incentives (e.g. tax or carbon credits), enhanced training of installers, improved installation efficiency as increasing

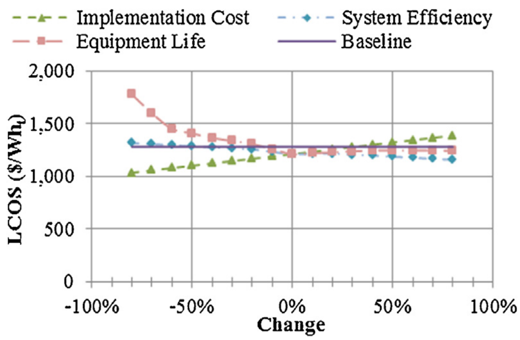

Fig. 15. Coastal multifamily sensitivity.

numbers of systems are deployed, or by improved technology. The sensitivity of the LCOS depends on the size of the GHX. The inland LCOS is more sensitive to increases in capital cost than to equipment life, due to the need for a larger GHX. The reverse is true for the coastal climate. The fact that this cost occurs only once through the 20-year analysis period shows the significance of the GHX component to the total system cost, especially in larger systems.

As the ratio of HVAC energy use to total facility energy use increases (as in the case of inland lodging), system efficiency produces increasingly significant changes in LCOS. The overall system efficiency is comprised of multiple factors including but not limited to: GTHP COP, pumping system efficiency (affected by piping design and pump mechanical efficiency), and GHX thermal performance (affected by ground conditions, loop size and borehole performance). While an identical ground type was assumed in this work, ground properties can vary significantly between climates and geographical locations. In general, soils with lower conductivities necessitate the installation of longer GHX. Moisture content or the presence of ground water typically enhances GHX performance beyond heat diffusion in dry soil.

As equipment life is decreased, LCOS increases dramatically since replacement systems were installed with either the same or increased efficiency, but at the expense of higher total capital costs that do not justify the energy savings. These two competing factors produced a relatively constant LCOS as equipment life increases, but a rapid increase in LCOS as equipment life decreases.

5. Conclusions and recommendations

The total levelized cost of service appears to be comparable for the GTHP and PTHP, with some advantage for the GTHP due largely to maintenance cost savings and, depending on the climate and building type, lifetime capital cost savings and energy cost savings. Smaller facilities situated in mild climates benefit from levelized capital cost reductions, but minimal energy savings and energy cost savings. Larger facilities situated in more extreme climates benefit from higher energy efficiency but lower levelized capital cost savings due to longer GHX requirements to meet peak loads. In all cases, the energy LCOS savings were estimated to be lower than the maintenance LCOS savings. The total LCOS savings, which were estimated to be between \$1.7/yr-m^2 and \$3.6/yr-m^2, were impacted by a number of assumptions that would need to be verified.

For the modeled buildings, the GTHP system was estimated to reduce demand by 7%-34% during peak cooling and heating periods. In terms of total energy savings, the GTHP was estimated to use between 4% less and 1% more electrical energy than the baseline depending on the magnitude of space loads and climate. The estimated LCOS reduction for the inland facilities under TOU rate schedule was higher than it would be under a non-TOU rate schedule. For the coastal facilities, the estimated LCOS reduction under TOU schedule was lower than it would be under a non-TOU schedule. From the magnitude of estimated demand and cost reduction, the GTHP technology can significantly benefit the utility during peak cooling period.

When the GTHP is compared against natural gas-based heating systems, energy savings should be evaluated on a source energy basis to account for off-site fuel-to-electricity conversion losses. As heating load becomes more dominant, energy savings on a site basis can erroneously favor the GTHP. Furthermore, the cost benefit of the GTHP can decrease with higher electricity prices, vice versa.

Sensitivity analyses highlight the importance of reducing system cost and ensuring long equipment service live. As HVAC energy use increases relative to the total facility energy use, system efficiency becomes an increasingly important factor. For the multifamily facilities, as equipment live increases, LCOS increases slightly from the nominal cast (0% change) due to the tiered utility rate structure imposing a higher cost to increasing electrical energy use.

The results of this work suggest that in order to achieve energy savings, application of GTHP will be limited to more extreme climate where differences between air and ground temperature are large relative to mild climates. Results suggest the potential for overall cost savings with wider deployment of GTHP technology, at least within the two building types analyzed in the model. In the cases studied here, however, the GTHP does not appear to offer significant advantages over PTHP unless substantially reduced maintenance costs are achieved. A long-term evaluation of the GTHP maintenance requirements will help determine the economic feasibility of the technology. The projected peak demand savings should be verified as a future study using monitoring data from the pilot site.

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