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Assessing the impacts of air-sealing on the sizing, operation, and economic feasibility of ground-source heat pumps for electrifying single-family houses in the US

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ABSTRACT

According to recent studies and reports, in single-family houses (SFHs), air-sealing can significantly lower the thermal loads for space heating and cooling. Thus, air-sealing in SFHs could reduce the required size and cost of ground source heat pump (GSHP) systems for electrifying SFHs. This study investigated the costs and benefits of integrating air-sealing with GSHPs for retrofitting existing SFHs when compared with air-source heat pumps. A whole building energy simulation tool integrated with an advanced design tool for modeling ground heat exchangers was used to calculate changes in required GSHP capacity, total borehole length, and building energy consumption with and without air-sealing in SFHs in 16 US climatic regions. The results from this study showed that reducing outdoor air infiltration from 0.8 air changes per hour (ACH) to the minimum ventilation requirement (0.35 ACH) can significantly reduce borehole length (up to 55 %), GSHP capacity (up to 48 %), and total heating electricity reduction, especially in cold climates (up to 44 %). The results also showed that for airtight homes (0.03 ACH infiltration) with a direct outdoor air system, the minimum required borehole length, GSHP capacity, and total heating electricity consumption can be reduced up to 70 %, 68 %, and 67 %, respectively, when compared with SFHs with 0.8 ACH infiltration. Moreover, the life cycle cost analysis showed that air-sealing in conjunction with a GSHP is more profitable than replacing the existing system with an air-source heat pump, even without any incentives for most climatic regions in the US (except for some hot regions).

1. Introduction

Buildings account for a significant share of world energy usage. In the US, for example, the buildings sector accounts for about 71 % of electricity use and 40 % of all US primary energy use [1]. Residential and commercial buildings account for 37 % and 34 %, respectively, of the total electricity use in the US [1]. In the European Union, buildings consume 40 % of all energy [2]. In 2022, building heating and cooling represented 13 % of total primary energy use, 15 % of total electricity use, and 12 % of total CO_2 emissions (including those from the electric power sector) in the US [3]. Therefore, attaining the global carbon reduction target

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Nomenclature

ACH	Air changes per hour
AIRR	Adjusted internal rate of return
$Area_{\text{floor}}$	Floor area
$Area_{\text{Leakage}}$	Leakage area
ASHP	Air source heat pump
$ASHP_{\text{cost}}$	Price of ASHP unit
BLCC	Building Life Cycle Cost calculator
C_s	Coefficient of stack-induced infiltration
C_w	Wind coefficient
$Cost_{\text{air sealing}}$	Air-sealing cost
$Cost_{\text{ASHP}}$	Capital cost for ASHP
$Cost_{\text{GSHP}}$	Capital cost for GSHP
$Cost_{GSHP+AS}$	Cost for the GSHP scenario with 0.35 ACH
CZ	Climate zone
DOAS	Dedicated outdoor air system
DOE	Department of Energy
ELA	Effective leakage area
GHE	Ground heat exchangers
GHE_{cost}	Cost of GHE
GSHP	Ground source heat pump
IECC	International Energy Conservation Code
ITC	Investment Tax Credit
$Labor\_Cost_{\text{ASHP}}$	Labor cost for ASHP installation
$Labor\_Cost_{\text{WAHP}}$	Labor cost for GSHP installation
LCA	Lifecycle cost analysis
N	Number of years
N_{floor}	Number of floors
OA	Outdoor air
R	Reinvestment rate
SFH	Single-family house
TMY3	Typical meteorological year version 3
v	Wind speed
WAHP	Water-to-air heat pump
$WAHP_{\text{cost}}$	Cost of WAHP
WAP	Weatherization Assistance Program
Y	Payback period in years
ΔE	Savings in energy cost attributable to the alternative case
ΔE_t	Savings in energy cost attributable to the alternative at year t
ΔI	Additional investment cost required for the alternative case
$\Delta Repl$	Additional capital replacement costs required for the alternative case
ΔT	Temperature difference between indoor and outdoor

depends in large part on how energy-efficient buildings are. Researchers must understand the amount of energy loss resulting from outdoor air (OA) infiltration because it accounts for one-third of the heating energy demand [4]. The average American house leaks two to four times more than a newly constructed house that was built based on building codes [5,6].

Currently, fossil fuels dominate space heating [7] in the US. The US Government has recently set a target to reduce greenhouse gas emissions by 2030 by 50 % measured against 2005 levels and to become a carbon-neutral economy by 2050 [8]. Air-source heat pumps (ASHPs) are the most common type of electric-driven heat pump in the marketplace to replace fossil fuel–based heating sources. The heating/cooling capacity and efficiency of ASHPs depend on the OA conditions when they are operating. ASHPs are usually equipped with electric resistance heaters to provide supplemental heating. The electric resistance heaters are turned on when the outdoor temperature is low and the heating demand is high. These heaters result in high power draws. Recent studies [9–11] indicated that the replacement of gas-fired furnaces with ASHPs in the residential sector would result in higher annual electricity consumption and a shift in peak electricity demand from summer to winter. Such a shift could substantially change how the power grid operates and, as a result, would require substantial new investments in the electric power infrastructure. For instance, a recent study showed that the complete electrification approach (using an ASHP with supplementary electric resistance heaters) could require a 70 % increase in nationwide electricity system capacity [12]. Adopting ground source heat pump (GSHP) technology is one feasible solution for reducing the requirements of expanding the capacity and transmission of electric power systems in the US.

GSHPs have been used in both residential and commercial buildings in all 50 US states [13]. Because of the relatively steady temperature of the ground, GSHPs are more energy-efficient throughout the year than ASHPs when providing space heating and cooling to buildings. A schematic diagram of a GSHP system in a single-family house (SFH) is shown in Fig. 1. For each kilowatt-hour of cooling or heating outcome, a GSHP presently needs 0.22–0.35 kWh of electricity, which is 30%–50 % lower than the seasonal average power usage for providing the same amount of heating or cooling using air-to-air heat pumps that employ OA as a heat sink/source [14]. Previous studies e.g., Ref. [15–19] reported that GSHPs are typically 20%–40 % more energy-efficient than conventional heating and cooling systems, which leads to significant energy cost savings for building owners or occupants. Furthermore, replacing an ASHP with a GSHP will reduce heat released from buildings considerably during the summer, thereby reducing the magnitude of urban warming effects [20–22].

However, the adoption of GSHPs is hindered by their high initial cost mostly because of the cost of drilling boreholes in the ground for installing ground heat exchangers (GHEs). One strategy to lower the initial cost of a GSHP system would be to lower the heating and cooling energy demand of a building by considering envelope improvements, thereby reducing the size of the GSHP system and length of the GHE. Because OA infiltration contributes significantly to heating and cooling loads [4], it can significantly influence the GSHP system's capacity (thereby affecting the required total borehole drilling length) and energy utilization. The reduced size of a GSHP system can also lower the peak electricity demand in the winter resulting from the electrification of space heating in buildings. To foster wider adoption of GSHPs, the US Government provides financial incentives that can compensate investors 30 % of the total cost for implementing a GSHP system through federal tax credits or other payments. Similar but smaller tax credits are also available for air-sealing [23,24].

In SFHs, air leakage can be reduced by an average of 25%–30 % by sealing minor gaps and holes in the building's envelope, preventing the uncontrolled transfer of air and heat between the internal and external environments [25,26]. Additional reductions in air leakage can be achieved by other envelope improvements, such as adding insulation and upgrading windows [27]. Decades of building infiltration reduction and related program evaluations confirm the effectiveness and reliability of building infiltration reduction to reduce overall energy use and peak heating load [28,29]. In the US, the US Department of Energy's Weatherization Assistance Program (WAP) has supported residential building energy efficiency retrofits, with air-sealing often being the first retrofit specified, for nearly five decades [30]. Building upon the energy use reduction foundation laid by WAP in income-qualified populations, US state governments, utility providers, municipalities, territories, and sovereign nations offer energy-efficiency incentive programs (e.g., cost-saving, rebates) to the general population within their respective geographic areas [31]. The pervasive and persistent inclusion of building infiltration reduction among energy-efficiency programs solidifies the conclusion that building infiltration reduction consistently and reliably results in lower energy demand by the treated building and, thus, reductions in energy use and peak energy demand. Therefore, air-sealing retrofits can reduce the required GSHP system capacity for the treated home, reducing the number of boreholes as well as the cost of installing the GHE and the overall cost of the GSHP system, which could potentially lead to a shorter payback period after GSHP installation.

Unfortunately, previous studies have not given any attention to identifying the effect of air-sealing homes on electrifying residential space heating with GSHPs. As an initial step in this research direction, the current study estimated the costs and benefits of integrating air-sealing with GSHPs for retrofitting existing SFHs in different US climate zones (CZs). The study performed a life cycle cost analysis (LCA) for GSHP system installations (without and with air-sealing) compared with ASHP installation as the baseline. This study employed a whole-building energy simulation tool integrated with an advanced design tool for the GHE to determine changes in (1) GSHP capacity, (2) total borehole length, (3) building energy consumption, and (4) cost-effectiveness of the GSHP system installation with varying OA infiltration levels (0.8, 0.35, and 0.03 air changes per hour) in SFHs across 16 CZs in the US. The results of this study inform homeowners and decision-makers of the significance of integrating air-sealing in GSHP retrofits.

2. Methodology

This study used the US Department of Energy's prototype building models for a single-family detached house [32], which represents a set of identical 221 m^2, two-story houses that use various heating systems and foundation types. The characteristics of these prototype buildings, such as the insulation level of the building envelopes in each CZ, were specified following one of the editions of the *International Energy Conservation Code* (IECC) based on the vintage of the building. A set of prototype models created following the 2006 edition of IECC were used in this study for 16 US CZs.

An ASHP[1] and slab-on-grade foundation were specified in these models. The Typical Meteorological Year version 3 (TMY3) weather data of representative cities (listed in section 2.1) for the 16 CZs were used in this study. For each base case, three alternative scenarios of GSHP retrofits were modeled, each with an identical GSHP system but different OA infiltration levels. Each GSHP retrofit scenario was modeled following a three-step process. The first step was to conduct an initial simulation using whole-building energy simulation software, called EnergyPlus [33], to estimate the hourly thermal loads of the GHE. Default values of g-functions, a set of precalculated response factors of vertical bore GHEs [34], were used in this step, along with other borehole design parameters (listed in Table 1). The second step employed an innovative design tool, called GHEDesigner [35], to determine the layout of the borehole field

[1] The ASHP simulated in the prototype building models had a nominal coefficient of performance of 3.69 for heating and 4.07 for cooling. The simulated ASHP had a supplemental electric resistance heater. The electric resistance heater turned on when the outdoor ambient temperature was below 7.2 °C (45 °F). It worked along with the ASHP until the outdoor ambient temperature dropped below −17.78 °C (0 °F). Then, the ASHP was shut off, and only the electric resistance heater provided space heating.

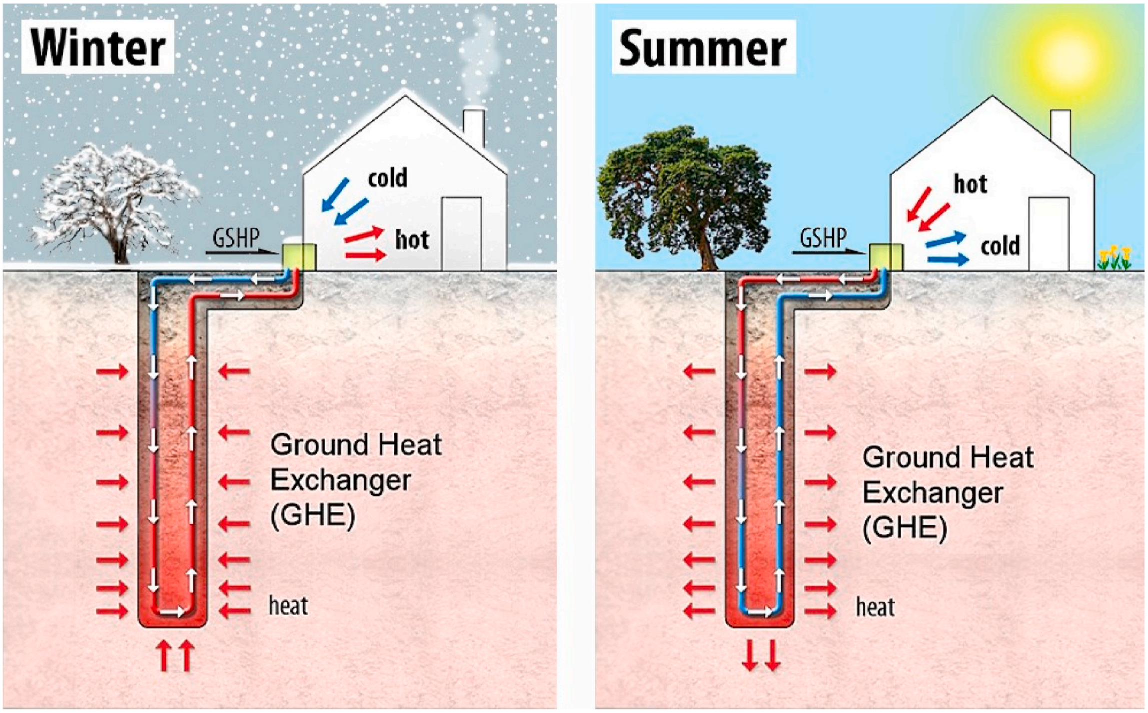

Fig. 1. Schematic diagram of a GSHP system [after [61]].

and calculate the required borehole length. GHEDesigner also calculated g-functions of the specified GHE design. In the final step, the whole-building energy simulation that adopted the final design of the GHE (including the associated g-functions) was performed to predict the building energy usage of the GSHP system. The results from the EnergyPlus simulation were used to perform an LCA for the GSHP system using the Building Life Cycle Cost (BLCC) calculator [36].

2.1. Whole-building energy simulation

This study used EnergyPlus to predict heating and cooling electricity usage and the capacity of the GSHP system. EnergyPlus is an open-source platform developed by the US Department of Energy's Building Technologies Office as part of their building energy modeling program portfolio. Individual components of EnergyPlus and the modeling package as a whole have been validated in numerous previous studies [37–43]. EnergyPlus can simulate the hourly and subhourly performance of a building and its energy systems (including space heating, space cooling, and water heating) over an entire year (or multiple years), accounting for the complexities of building geometry, materials, occupancy, operation, and local climate.

A set of prototype models for a SFH created following the 2006 edition of IECC were used as base cases for all 16 US CZs. An ASHP and slab-on-grade foundation were specified in these base cases. For this study, the outside boundary condition of the floor construction of the SFH was set as "Ground."[2] In each CZ, the following three scenarios of OA ventilation were modeled along with replacing the ASHP with a GSHP system.

- Leaky/high infiltration: keep base case OA infiltration of 0.8 air changes per hour (ACH), representing a typical residential construction (Margaret et al., 2022).
- Low Infiltration: reduce OA infiltration to 0.35 ACH, representing a house with air-sealing treatment and meeting the minimum OA ventilation requirement of ASHRAE Standard 62.2 (ASHRAE 2016).
- Dedicated OA system (DOAS): provide the minimum required OA using the DOAS and reduce OA infiltration to 0.03 ACH or below, representing air-tight, new construction.

[2] The default prototype building models use outside boundary condition object as "GroundSlabPreprocessorAverage". Changing the outside boundary condition from "GroundSlabPreprocessorAverage" to "Ground" causes a difference in total electricity usage for heating and cooling ranging from 1 % to 14 % for the prototype building using an ASHP depending on CZs. The current study used a Python module, Eppy [62], for conducting the parametric simulation. The default prototype building models need EnergyPlus preprocessing software to execute "GroundSlab-PreprocessorAverage." Unfortunately, the latest version of Eppy does not support EnergyPlus preprocessing software while running EnergyPlus simulation. Therefore, the outside boundary condition was changed to "Ground" in this study.

Table 1
Vertical borehole GHE design parameters.

Parameter	Default value	Parameter	Default value
Borehole radius (m)	0.0762	Grout heat capacity (kJ/[m^3·K])	3900
U-tube pipe thickness (m)	0.0024	Ground conductivity (W/[m·k])	1.3
U-tube pipe outer diameter (m)	0.0267	Ground heat capacity (kJ/[m^3·K])	2347
U-tube distance (m)	0.025	Design flow rate (m^3/s)	0.000689
Pipe conductivity (W/[m·K])	0.3913	Bore spacing (m)	6.5
Pipe heat capacity (kJ/[m^3·K])	1770	Maximum GHE supply temp. (°C)	35
Grout conductivity (W/[m·k])	1.3	Minimum GHE supply temp. (°C)	−3

For modeling OA infiltration, the airflow network, which represented the air leakage in prototype models, was replaced with the effective leakage area method [44] to estimate the indoor–outdoor air exchange, accounting for wind and indoor–outdoor temperature difference, as expressed in Eq. (1):

$$Infiltration = \frac{Area_{\mathrm{Leakage}}}{1000}\sqrt{C_{\mathrm{s}}\Delta T + C_{\mathrm{w}}V^2}, \tag{1}$$

where.

C_s is the coefficient of stack-induced infiltration (0.00029 for two-story buildings)

C_w is the wind coefficient (0.000231 for two-story buildings with typical shelter caused by other buildings across the street)

ΔT is the temperature difference between indoors and outdoors.

V is the wind speed.

$Area_{\mathrm{Leakage}}$ is estimated based on the statical correlation developed by a previous study [6] based on floor area ($Area_{\mathrm{floor}}$) and number of floors (N_{floor}), as shown in Eq. (2). The effective leakage area method has been validated and used in several previous studies [45–47].

$$Area_{\mathrm{Leakage}} = \frac{Area_{\mathrm{floor}} \times ACH}{1000 \times N_{\mathrm{floor}}^{0.3}} \tag{2}$$

where ACH is the three air change per hour values (listed above) considered in the study.

A GSHP system and a DOAS were added in the prototype building model to replace the original ASHP. The modeled GSHP system included an extended-range water-to-air heat pump (WAHP), a vertical bore GHE, and a circulation pump. The heating and cooling coefficients of performance of the WAHP were 4.0 and 6.5, respectively, at the rating conditions for ground loop application specified in the ANSI/AHRI/ASHRAE/ISO Standard 13256-1, *Water-to-Air and Brine-to-Air Heat Pumps—Testing and Rating for Performance* [48]. The entering water temperature of the WAHP was from the supply water temperature of the GHE, and the effect of the GHE supply temperature on the heat pump efficiency was modeled in the simulations. The default vertical borehole GHE design parameters used in the simulation are presented in Table 1. Table 2 lists the undisturbed ground temperature at each representative city of the 16 CZs. The undisturbed ground temperatures are from a dataset created by Ref. [49].

The prototype building model used design day heating and cooling loads to autosize the WAHP. This method might not always size the heat pump with sufficient capacity. In some cases, the unmet hours (i.e., the hours when the room temperature is not maintained at the set point) could be more than 300 h, which is the maximum number recommended by ANSI/ASHRAE/IES Standard 90.1–2010's *Performance Rating Method Reference Manual* [50]. As shown in Fig. 2, an iterative sizing procedure was implemented in this study to increase heat pump capacity gradually (10 % in each iteration) until the annual unmet hours were less than 300 h. The design parameters of the GHE, including the undisturbed ground temperature, and the thermal loads of the GHE predicted with an initial simulation of the GSHP system, which used a roughly sized GHE, were used to more accurately size the GHE using GHEDesigner version 1.3 [35]. The sized GHE, including the layout of the borehole field, number of boreholes, the depth of each borehole, and the associated g-functions, were used to update the building energy simulation model to perform the final simulation. After the final simulation was completed, the simulation results were stored, and the process was repeated until all the three OA ventilation scenarios were simulated for each of the 16 CZs, as depicted in Fig. 2.

2.2. Economic analysis

The LCA of installing a GSHP system in an existing SFH without and with air-sealing (i.e., with 0.8 ACH and 0.35 ACH OA infiltration, respectively) was performed relative to the base case scenario of ASHP installation (with 0.8 ACH infiltration). The GSHP system in an airtight new construction (fully air-sealed with 0.03 ACH and using a DOAS for OA ventilation) was not included in this LCA because of limited available data for estimating the cost of this scenario. For the LCA, the adjusted internal rate of return (AIRR) was calculated, which is a measure of the annual percentage yield from an investment over the study period. If the AIRR is greater than the real discount rate, the investment is considered economically feasible. The discount rate was determined to be 3 % for this study based on National Institute of Standards and Technology Handbook 135 [51].

The LCA was conducted using the BLCC calculator [52]. BLCC accounts for nonconstant energy escalation rates based on the US Energy Information Administration's projected energy prices [53]. The 2021 annual average electricity price was used in this analysis

Table 2
Undisturbed ground temperature at each of the representative cities of the 16 CZs.

CZs	Representative cities	Undisturbed Ground Temperature (°C)
1A	Miami, Florida	24.0
2A	Houston, Texas	21.2
2B	Phoenix, Arizona	25.6
3A	Atlanta, Georgia	17.8
3B	Las Vegas, Nevada	21.6
3C	San Francisco, California	16.2
4A	Baltimore, Maryland	14.4
4B	Albuquerque, New Mexico	16.4
4C	Seattle, Washington	13.1
5A	Chicago, Illinois	12.5
5B	Denver, Colorado	12.9
5C	Port Angeles, Washington	13.9
6A	Minneapolis, Minnesota	9.1
6B	Helena, Montana	9.8
7	Duluth, Minnesota	6.1
8	Fairbanks, Alaska	2.4

for the current/starting year (Table 3). The lifetime used in the LCA was 40 years because the GHE, which is made of high-density polyethylene, can have a lifespan in the ground of at least 40 years, as guaranteed by high-density polyethylene manufacturers.

The capital cost for the ASHP was calculated using Eq. (3). The cost for purchasing an ASHP and the associated labor cost for installation were calculated based on the current market prices. ASHP units were chosen from a supplier [54] based on the capacity needed (from the simulation results) for the corresponding cities. The price of the ASHP unit ($ASHP_{\text{cost}}$) in each city is discussed in Section 3.6. The associated labor cost for installation ($Labor\_Cost_{\text{ASHP}}$) was assumed to be 53 % of the ASHP unit price [55].

$$Cost_{\text{ASHP}} = ASHP_{\text{cost}} + Labor\_Cost_{\text{ASHP}} \tag{3}$$

The capital cost of a GSHP system ($Cost_{\text{GSHP}}$) is the sum of the GHE cost, WAHP cost, and associated labor cost, as expressed in Eq. (4). The GHE cost was assumed to be \$15/ft of borehole linear length, which is based on 2013 prices [13]. After adjusting for inflation, the GHE cost (GHE_{cost}) was \$19.65/ft in 2023 based on the Consumer Price Index Inflation Calculator [56]. The associated labor cost for the GHE was already incorporated in the price per length (\$19.65/ft). The air-sealing cost ($Cost_{\text{air sealing}}$) for a typical SFH in the US ranged from \$0.90/ft^2 to \$2.03/ft^2 [57], including labor costs. This study used an average value of \$1.5/ft^2 for air-sealing, and that value was added to the total cost for the scenario with 0.35 ACH ($Cost_{\text{GSHP+AS}}$), as shown in Eq. (5). The study conducted a 40-year LCA because the lifespan of a GHE is typically 40 years. However, the lifespan of a WAHP is 20 years. Therefore, in addition to the initial capital cost, the replacement cost of a WAHP ($WAHP_{\text{cost}}$) after 20 years was also considered in this study for both an ASHP and GSHP with a 0 % annual rate of increase compared with the starting year cost.

$$Cost_{\text{GSHP}} = GHE_{\text{cost}} + WAHP_{\text{cost}} + Labor\_Cost_{\text{WAHP}} \tag{4}$$

$$Cost_{\text{GSHP+AS}} = GHE_{\text{cost}} + WAHP_{\text{cost}} + Labor\_Cost_{\text{WAHP}} + Cost_{\text{air sealing}} \tag{5}$$

This study also analyzed the impact of the Investment Tax Credit (ITC) provided by the US Government on the cost-effectiveness of GSHP deployment. ITC is a financial incentive that can compensate investors on 30 % of the total cost for implementing a GSHP system through tax credits or other payments. This study considered that ITC results in a 30 % reduction in the total cost of the GSHP system (in the real scenario, these credits were received at time of tax returns). Similarly, a 30 % ITC is also available for an ASHP (with a cap of \$2000 and excluding labor cost) and air-sealing (with a cap of \$1200, not excluding labor cost). ITCs for the ASHP and air-sealing (with their corresponding caps) were also considered in the LCA. This study did not consider the maintenance or salvage costs of the systems in the LCA. BLCC estimated AIRR using Eq. (6). All cost values in Eq. (6) are in the present value. To estimate the AIRR, Eq. (6) accounts for investment cost, savings, lifetime of the considered equipment, additional costs, and reinvestment rates. If the AIRR was greater than 3 %, the investment for GSHP retrofit was considered economically feasible compared with the ASHP retrofit. In Eqs. (6) and (7), the baseline for the economic analysis was an ASHP system for a leaky building with 0.8 ACH OA infiltration. Alternative cases were a GSHP system for a leaky (0.8 ACH) and an air-sealed (0.35 ACH) building.

$$AIRR = (1 + R) \times \left(\frac{\Delta E}{\Delta I + \Delta Repl} \right)^{\frac{1}{N}} - 1 \tag{6}$$

where.

R is the reinvestment rate

N is the number of years

ΔE is the savings in the annual energy cost attributable to the alternative case

ΔI is the additional investment cost required for the alternative case

$\Delta Repl$ is the additional capital replacement costs required for the alternative case

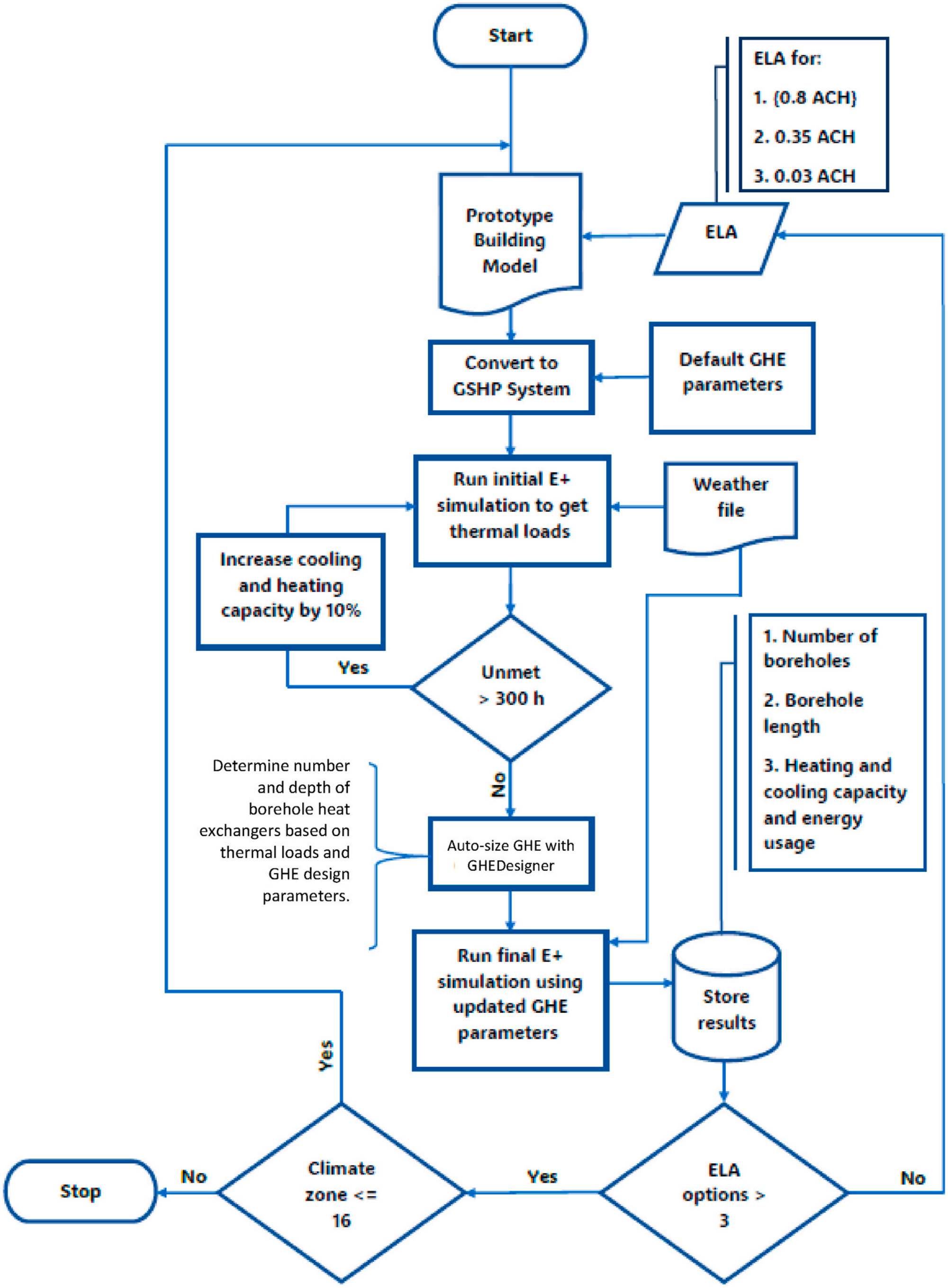

Fig. 2. Flowchart of the procedures for modeling GSHP systems in the prototype SFH under the three OA ventilation scenarios at each of the 16 CZs.

The discounted payback period is also calculated with BLCC, and it represents the number of years required for the cumulative savings from an investment to pay back the investment costs and replacement costs, considering the time value of money. Eq. (7) shows the equation that is used implicitly to calculate the discounted payback period.

$$\sum_{t=1}^{y} \frac{\Delta E_t - \Delta Repl}{(1+R)^t} \geq \Delta I \tag{7}$$

where.

y is the payback period in years

Table 3
Annual average electricity price of the corresponding states.

CZ	Representing cities	State	Electricity price (cent/kWh)
1A	Miami	Florida	10.67
2A	Houston	Texas	9.14
2B	Phoenix	Arizona	10.73
3A	Atlanta	Georgia	10.43
3B	Las Vegas	Nevada	8.58
3C	Los Angeles	California	19.65
4A	Baltimore	Maryland	11.48
4B	Albuquerque	New Mexico	9.79
4C	Seattle	Washington	8.75
5A	Chicago	Illinois	10.14
5B	Denver	Colorado	10.9
5C	Port Angeles	Washington	8.75
6A	Minneapolis	Minnesota	11.08
6B	Helena	Montana	9.5
7	Duluth	Minnesota	11.08
8	Fairbanks	Alaska	20.02

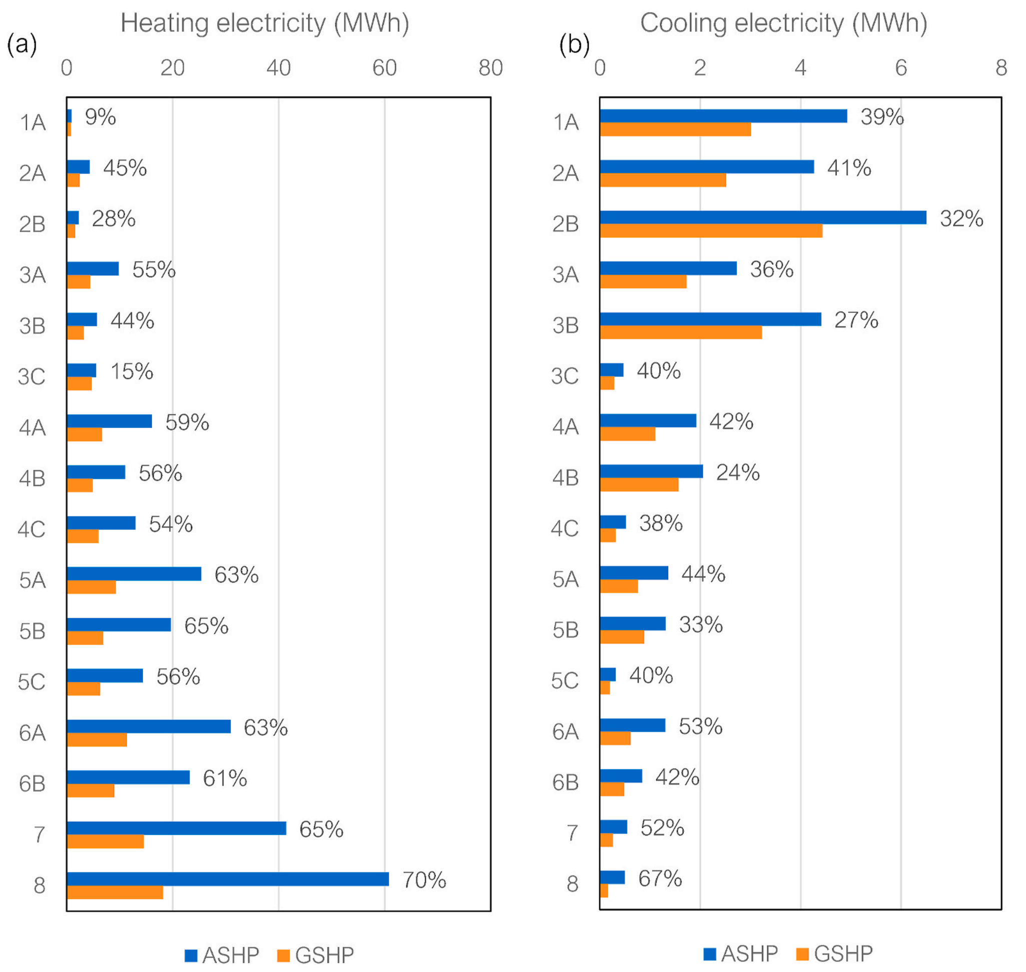

Fig. 3. (a) Heating electricity and (b) cooling electricity usage for the SFH at various climates resulting from using ASHP and GSHP systems, respectively (with ELA corresponding to 0.8 ACH). The percentage reduction in energy usage comparing the GSHP with the ASHP is also labeled in the figure.

ΔE_t is savings in annual energy cost attributable to the alternative at year t

3. Results

3.1. Energy use with ASHP versus GSHP system

Fig. 3 shows the heating electricity and cooling electricity usage for the SFH at various climates resulting from using ASHP and GSHP systems (with effective leakage area [ELA] corresponding to 0.8 ACH). Fig. 3(a) shows that a GSHP can reduce cooling electricity usage by 24 %–67 % depending on the locations of the SFH. This reduction occurs because the undisturbed ground temperatures are lower than the ambient air temperatures in the cooling season, so GSHPs run more efficiently than ASHPs. As a result, the GSHP consumes less electricity to maintain the indoor condition at the thermostat set point. For instance, for hot cities such as Phoenix (CZ 2B), an ASHP required 6.50 MWh electricity for cooling, whereas a GSHP consumed only 4.43 MWh electricity to meet the same cooling load, which was 32 % less than that consumed by the ASHP. In cities with moderate or colder climates, the percentage reduction for cooling electricity was found to be between 30 % and 70 %; however, the absolute difference was relatively smaller (when compared with cities in hot climates) because cooling needs were not predominant there.

Fig. 3(a) compares the heating electricity usage between the ASHP and GSHP at various locations. As shown in this figure, the GSHP reduced heating electricity usage significantly (between 56 % and 70 %) in cold climates (CZs 5A, 5B, 5C, 6A, 6B, 7, and 8). In the heating season, the temperature difference between the indoor air (thermostat set point) and OA in these regions was considerably higher than the temperature difference between the indoor air (thermostat set point) and the undisturbed ground temperature, thereby resulting in a higher heating efficiency for the GSHP and lower electricity usage. For instance, in CZ 8, the heating electricity required to meet the thermostat condition was 60.79 MWh (supplemental electric resistance heating turned on once the ASHP exceeded capacity and worked simultaneously along with the ASHP), whereas the GSHP only consumed 18.16 MWh (no supplemental heating was needed) to meet the same heating demand, thereby resulting in an electricity usage reduction of 70 % for heating. Furthermore, space heating electricity usage was also reduced by the GSHP in regions with a hot climate, but the magnitude was smaller. When combining both cooling and heating, the total electricity usage of a GSHP was significantly lower than that of the ASHP, especially in regions with a cold climate.

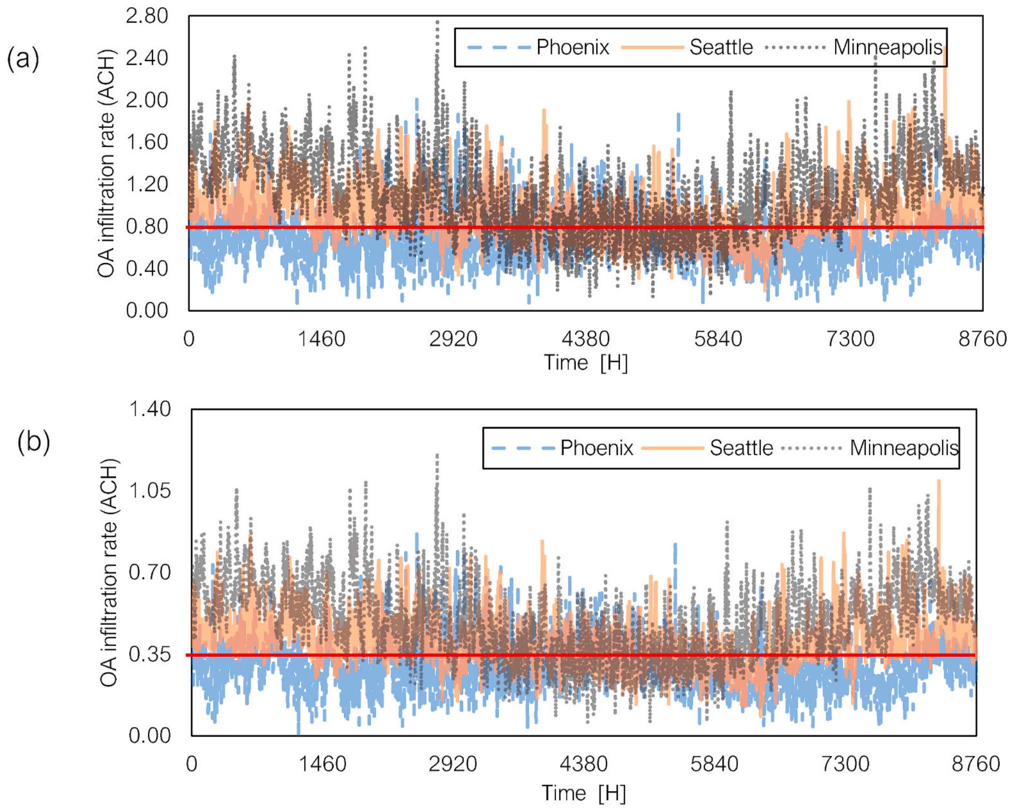

Fig. 4. Hourly OA infiltration rate for (a) high-infiltration (0.8 ACH) and (b) low-infiltration (0.35 ACH) SFHs modeled in this study.

3.2. Hourly OA infiltration rates

Although this study used the same ELA for each OA ventilation scenario in each city, the hourly OA infiltration rate varied depending on environmental factors, such as OA temperature and wind speed, as expressed in Eq. (1). To understand the actual OA brought into the SFH owing to infiltration at different CZs, this study compared the hourly OA infiltration rate calculated with EnergyPlus for the prototype SFH with an identical ELA in Phoenix (hot climate), Seattle (mild climate), and Minneapolis (cold climate). Fig. 4 shows the calculated hourly OA infiltration rate in ACH for the high (0.8 ACH) and low (0.35 ACH) OA infiltration scenarios. In general, with the same ELA, the OA infiltration rate was higher in winter than in summer because of higher wind speed and a larger outdoor–indoor temperature difference in winter. Among the three cities, Phoenix had the lowest hourly OA infiltration rate. The annual average OA infiltration rate of the modeled SFH in Phoenix was 0.3 and 0.68 ACH for the low- and high-infiltration scenarios, respectively. The annual average OA infiltration rate in Minneapolis was 0.48 and 1.1 ACH for the low- and high-infiltration scenarios, respectively. In the case of Seattle, these values were 0.40 and 0.92 ACH for the low- and high-infiltration scenarios, respectively. In contrast, the DOAS delivered OA at a constant rate of 0.043 m^3/s (which corresponds to 0.32 ACH). Together with the 0.03 ACH OA infiltration, the total OA ventilation rate was 0.35 ACH, which met the minimum ventilation requirement recommended by ASHRAE 62.2 (2016). The fluctuation of the OA rate will be minimal for SFHs with DOAS.

3.3. Impact of air-sealing on GSHP energy usage

Fig. 5 shows absolute values and percentages of changes in cooling electricity consumption resulting from reducing the OA infiltration rate. The results shown in Fig. 5 are the difference in energy usage (and percentage of energy savings) between the results of the two reduced infiltration cases and the baseline 0.8 ACH case. The baseline cooling energy use is shown in Fig. 3(b). The reduction of OA infiltration led to a 10%–25 % reduction in space cooling electricity usage in hot climates (1A through 3B). In regions with moderate or cold climates, OA infiltration helped to reduce the indoor temperature during summer months because the OA temperature in these regions was mostly within thermostat set points in the summer. Therefore, reducing OA infiltration increased cooling electricity usage. However, notably, even though the cooling electricity penalty was high in terms of the percentage of changes, the baseline cooling electricity use and the increase in electricity consumption owing to the reduced OA infiltration in these regions were small, as shown in Fig. 5(a).

Fig. 6 shows absolute values and percentages of the reduction in heating electricity consumption resulting from reducing the OA infiltration rate. The results shown in Fig. 6 show the difference in energy usage (and percentage reduction) between the reduced infiltration cases and the baseline 0.8 ACH cases (as shown in Fig. 3(a)). Reducing OA infiltration reduced heating electricity usage for all CZs. As shown in Fig. 6(a), the magnitude of savings was higher for colder regions. By reducing OA infiltration from 0.85 to 0.35 ACH, the heating electricity use was reduced by more than 30 % except for CZ 2B, which had a reduction just a little short of the 30 %

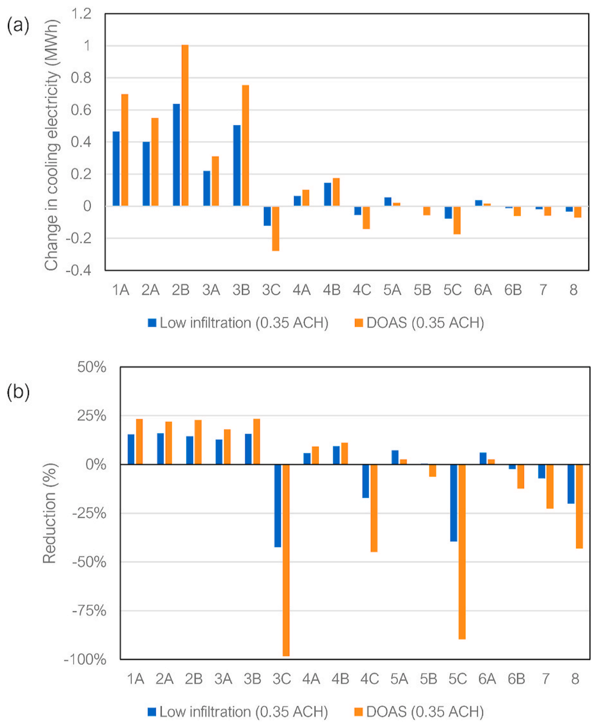

Fig. 5. (a) Absolute values and (b) percentages of changes in cooling electricity consumption resulting from reducing the OA infiltration rate.

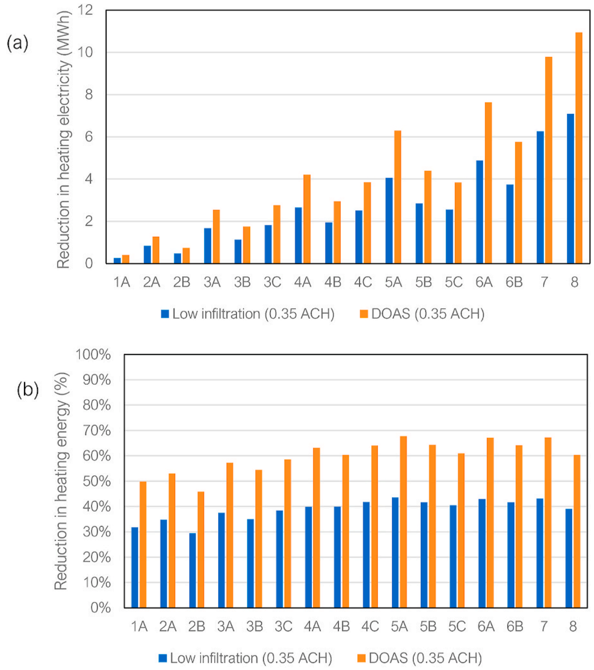

Fig. 6. (a) Absolute values and (b) percentages of reduction in heating electricity consumption resulting from reducing OA infiltration rate.

mark, as shown in Fig. 6(b). For the airtight SFH with DOAS, heating electricity usage was reduced by more than 50 %, with the highest reduction of 68 % occurring in CZ 5A.

Reduction in cooling electricity usage is smaller than the reduction in heating electricity usage. For instance, the maximum reduction in cooling electricity usage is in Phoenix (CZ 2B), which is 1 MWh, but the maximum reduction in heating electricity usage is about 11 MWh in Fairbanks (CZ 8). While combining cooling and heating electricity usage, the total annual electricity usage is reduced in all CZs by sealing the air leaks in the SFHs.

3.4. *Impact of air-sealing on required GSHP capacity*

To maintain the room temperature at set points all year long, a GSHP system must have heating and cooling capacities that are large enough to meet both the peak heating and cooling loads of the building. Fig. 7(a) shows the required capacity of a GSHP system resulting from three different OA infiltration/ventilation scenarios for the prototype SFH in various CZs. Fig. 7(b) shows the percentages of reduction in the required GSHP capacity resulting from reducing the OA infiltration/ventilation. Two phenomena were observed from these figures. First, the required GSHP capacity in a cold climate was larger than that in a hot climate. For instance, the required GSHP capacity for conditioning a leaky house (with 0.80 ACH OA infiltration) in CZ 2B was only 11.67 kW (determined by the peak cooling load), but it was 26.33 kW in CZ 7, which was determined by the peak heating load. Furthermore, the required GSHP capacity in CZ 7 was slightly higher than that of CZ 8 because the peak wind speed at CZ 7 (represented by Duluth, Minnesota) was 33

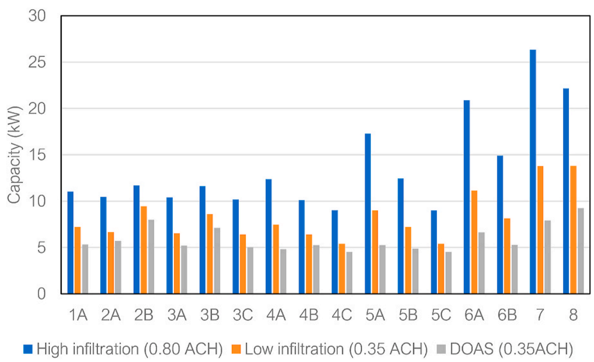

Fig. 7(a). Required capacity of GSHP system resulting under three different OA infiltration/ventilation scenarios for the prototype SFH in various CZs.

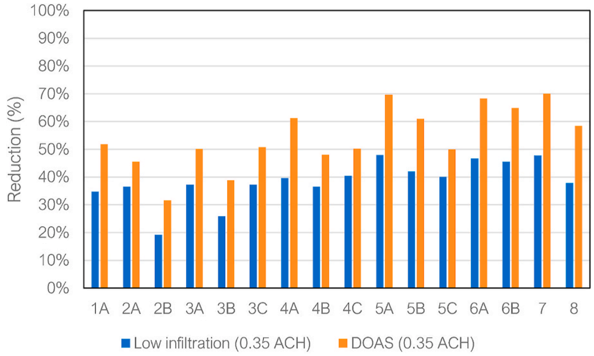

Fig. 7(b). Percentages of reduction in required GSHP capacity resulting from reducing OA infiltration/ventilation.

% higher than that at CZ 8 (represented by Fairbanks, Alaska) according to the TMY3 weather files used in the simulations of this study. However, under the low-infiltration and DOAS scenarios, the required GSHP capacity in CZ 8 was higher than that in CZ 7 because the colder OA temperature in CZ 8 weighed more on the heating load than the higher wind speed in CZ 7 when OA infiltration was reduced. The required GSHP capacity varied largely (from 11.0 to 26.3 kW) for conditioning leaky houses, but the variation was narrower (from 4.5 to 9.2 kW) for conditioning airtight houses, which used DOAS to provide minimum OA ventilation. Also, Fig. 7(b) indicates that the required GSHP capacity could be reduced by up to 48 % by reducing the OA infiltration rate to 0.35 ACH, and the reduction could be up to 70 % by providing the required minimum OA ventilation with a DOAS in airtight houses.

3.5. Impact of air-sealing on required total borehole length

Fig. 8(a) shows the required total borehole length resulting from different OA ventilation methods for the prototype SFH in various CZs. Fig. 8(b) shows the percentages of reduction in the required total borehole length resulting from a reduced OA infiltration rate. In hot and cold climates, such as CZs 2B and 7, respectively, the required total borehole length was more than 600 m for the leaky houses with 0.80 ACH OA infiltration. The long borehole length was due to a relatively high or low undisturbed ground temperature (25.6 °C in CZ 2B and 6.1 °C in CZ 7) and a large cooling or heating load. The result for CZ 8 is not shown in Fig. 8(a) because the required total borehole length obtained in CZ 8 was 2380 m for a SFH with high infiltration (0.8 ACH), 1080 m with low infiltration (0.35 ACH), and 636 m for an airtight house with DOAS. Although the 636 m length is consistent with results in other locations, the 2380 m borehole length is too long to be practical. In CZs 3C through 5C, which have mild weather, the required total borehole length was generally lower than 200 m. Fig. 8(a) clearly shows that reducing OA infiltration led to a shorter total borehole length required for meeting the thermal loads of the SFH in all CZs. Larger reduction ranging from 38 % to 73 % was observed in CZs with mild or cold climates (4C through 8).

3.6. Economic analysis for GSHP scenarios relative to ASHP scenario

Tables 4 and 5 show the needed capacity and associated costs of the GSHP and ASHP, respectively (including supplemental electric resistance heat), for maintaining unmet hours less than 300 h at each CZ assuming 0.8 ACH OA infiltration. As mentioned previously, the peak wind speed at Duluth, Minnesota (CZ 7) was 33 % higher than that at Fairbanks, Alaska (CZ 8). Therefore, the needed heat pump capacity at CZ 7 was slightly higher than that of CZ 8.

Fig. 9 shows the AIRR values for deploying a GSHP in the prototype SFH with and without air-sealing compared with using an ASHP

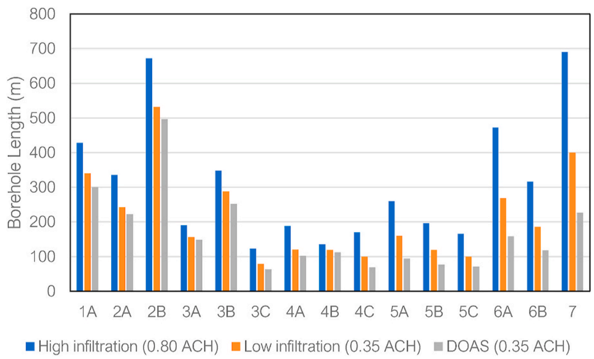

Fig. 8(a). Required total borehole length resulting from different OA ventilation methods for the prototype SFH in various CZs.

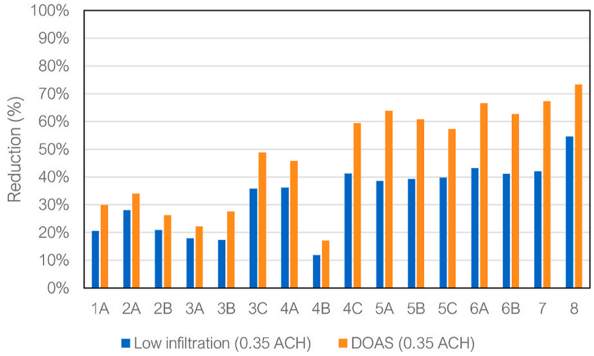

Fig. 8(b). Percentages of reduction in required total borehole length resulting from reduced OA infiltration rate.

Table 4
Required capacity and price of WAHP in each CZ for the GSHP system.

CZ	0.8 ACH		0.35 ACH	
	Capacity (ton)	WAHP price ($)	Capacity (ton)	WAHP price ($)
1A	3.5	3723	2.5	3276
2A	3	3564	2	3157
2B	3.5	3723	3	3564
3A	3	3564	2	3157
3B	3.5	3723	2.5	3276
3C	3	3564	2	3157
4A	4	4205	2.5	3276
4B	3	3564	2	3157
4C	3	3564	2	3157
5A	5	4460	3	3564
5B	4	4205	2.5	3276
5C	3	3564	2	3157
6A	6	5352	3.5	3723
6B	4.5	4333	2.5	3276
7	7.5	6690	4	4205
8	6.5	5798	4	4205

Table 5
Required capacity and price of ASHP in each CZ.

CZ	Capacity (ASHP [ton] + Resistance [kW])	ASHP price ($)
1A	2.5 + 8	3652
2A	2.5 + 8	3364
2B	3 + 8	3652
3A	2.5 + 15	3499
3B	2.5 + 10	3390
3C	2 + 8	3245
4A	2.5 + 15	3499
4B	2 + 10	3271
4C	2 + 8	3245
5A	2 + 15	3380
5B	2 + 15	3380
5C	2 + 8	3245
6A	3 + 20	3806
6B	2.5 + 15	3499
7	3 + 20	3806
8	3 + 25	3864

in each CZ with and without the ITC. The OA infiltration of the SFH using an ASHP was kept at 0.8 ACH without any air-sealing. Results shown in Fig. 9(a) do not consider the ITC, but the results shown in Fig. 9(b) do. Cases in the red-dotted box have an AIRR higher than 3 % (i.e., profitable) by using a GSHP (with and without air-sealing) instead of an ASHP. For the AIRR analysis, the scenario of airtight houses (with 0.03 ACH and DOAS) was not considered because it is very challenging to achieve 0.03 ACH OA infiltration by retrofitting existing SFHs. Fig. 9 indicates that for hot climates (CZs 1A, 2A, 2B, and 3B), the ASHP is preferable to choose over the GSHP irrespective of the ITC and airtightness of the house. This result is mainly because of the lower temperature difference between the outdoor

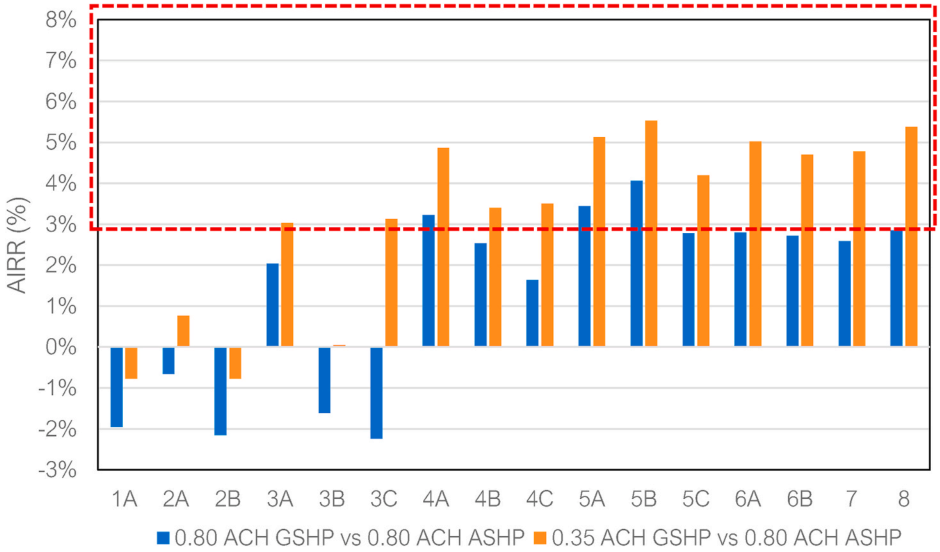

Fig. 9(a). AIRR values for deploying a GSHP in the prototype SFH with and without air-sealing compared with using an ASHP in each CZ without the ITC. (Note: The red dotted box in the figure indicates cases with >3 % AIRR). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

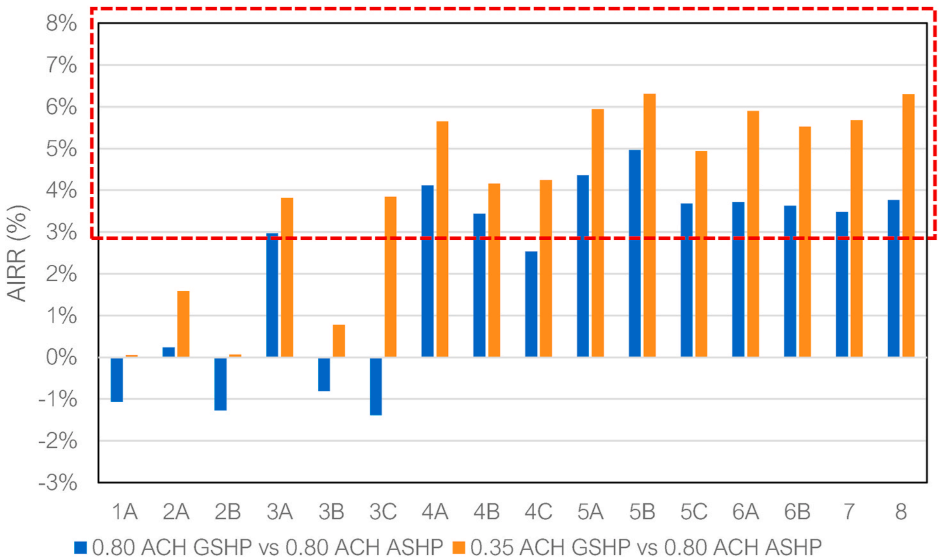

Fig. 9(b). AIRR values for deploying a GSHP in the prototype SFH with and without air-sealing compared with using an ASHP in each CZ with an ITC. (Note: The red dotted box in the figure indicates cases with >3 % AIRR). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and indoor air in summer in these CZs compared with that in winter in a cold climate. Therefore, savings in electricity usage from using a GSHP might not be good enough to cover its initial cost when compared with an ASHP. In CZ 3A, this study observed that for both the leaky houses (0.8 ACH) and air-sealed houses (0.35 ACH), using a GSHP was profitable if the resident took advantage of the ITC. Otherwise, without the ITC, GSHP retrofit combined with air-sealing was a profitable choice, but a GSHP alone was not, as shown in Fig. 9(a). However, in CZ 3C, using a GSHP was not profitable compared with using an ASHP unless air-sealing was performed along with the installation of GSHP system (with or without taking advantage of the ITC).

In CZs with mild or cold weather (4A through 8), this study observed that a GSHP combined with air-sealing is more profitable than only using a GSHP to replace an ASHP. In these CZs, no matter whether ITC was accounted for, the increased energy cost savings owing to air-sealing was more than offsetting the added cost for air-sealing. If the house was not air-sealed along with the GSHP retrofit, this method could still be economically feasible if the resident took advantage of the ITC.

Table 6 shows the discounted payback period for GSHP retrofit cases when compared with the ASHP retrofit case. For instance, in

Table 6
Discounted payback period of GSHP retrofit cases compared with baseline ASHP.

	GSHP without ITC		GSHP with ITC	
	0.8 ACH	0.35 ACH	0.8 ACH	0.35 ACH
1A	–	–	–	–
2A	–	–	–	–
2B	–	–	–	–
3A	–	40	–	24
3B	–	–	–	–
3C	–	37	–	26
4A	35	15	20	11
4B	–	32	31	21
4C	–	30	–	21
5A	19	13	18	9
5B	16	12	14	9
5C	–	22	28	16
6A	–	14	25	9
6B	–	17	28	12
7	–	15	29	10
8	–	13	26	9

"—" indicates that GSHP case is not economically feasible while comparing with ASHP.

the case of CZ 4A, it would take 11 or 15 years to overcome the additional cost of a GSHP in conjunction with air-sealing (0.35 ACH GSHP) when compared with the 0.8 ACH ASHP with or without the ITC. The savings obtained by the 0.35 ACH GSHP after 11 or 15 years were the additional profit obtained by the homeowner for choosing the 0.35 ACH GSHP over the 0.8 ACH ASHP with or without the ITC. The "—" in the table indicates that the GSHP case was not economically feasible (the additional cost for the GSHP was not recovered by the end of its lifespan) when comparing with the ASHP in that scenario.

The pattern of the results shown in Table 6 was identical to the result obtained in Fig. 9. These results indicated that in some hot climates, a discounted payback period occurred over the lifespan of the GSHP irrespective of the OA infiltration rate. However, for colder climates even without the ITC, the discounted payback period was almost less than half of the GHE lifespan. In regions with moderate weather, air-sealing in conjunction with a GSHP still remains the economically feasible choice. However, in CZs 4A and onward (except 4C), even without air-sealing, the homeowner can recover the additional cost of GSHP and start earning more savings after around 10 years if the homeowner can get the ITCs for GSHPs and air-sealing.

4. Discussion

High drilling costs and limited available land area for drilling boreholes are the challenges most homeowners face when considering a GSHP. The results of this study indicated that these challenges may be mitigated by combining air-sealing with a GSHP, especially in moderate and cold climates.

Although the currently available federal tax credits can make GSHP usage economically competitive in regions with mild or cold climates, as shown in Fig. 9(b), tax credits are a temporary measure and could be phased out in the next few years. This study indicated that combining air-sealing with a GSHP is a more cost-effective solution for electrifying SFHs than using ASHPs in regions with mild or cold climates even without the federal tax credits, as shown in Fig. 9(a). Therefore, the GSHP industry should consider this solution to sustain the adoption of GSHPs, which can help meeting the goal of decarbonization without drastically increasing the infrastructure for electric power generation and transmission [58].

The study had two main outcomes. Firstly, this work suggested that when building newer SFHs with GSHP systems, homeowners and policymakers should consider implementing airtight SFHs (in this case 0.03 ACH) with DOAS. Secondly, when retrofitting existing SFHs with GSHP systems, the air infiltration rate should be reduced, if possible, to 0.35 ACH (typically only newly constructed homes achieves 0.03 ACH, and retrofits have practical challenges in the present scenarios). The findings of this study indicated that when considering building electrification, these methods are more cost-effective than ASHP deployment in moderate and cold climates.

Even though Fairbank, Alaska, was included in this study to show an extreme condition, it is not practical to drill a 2000 m borehole to keep the GHE supply temperature higher than -1 °C. The g-function does not account for phase change of water in the ground formation, which could release latent heat, so the 2000 m borehole result is most likely oversized with the current GHE design tool (GHEDesigner).

The proposed approach in this study can also apply to ASHPs (i.e., building efficiency improvements before installing new systems, such as ASHPs or GSHPs). Although air-sealing reduces thermal loads and thus can also downsize the ASHP, the impact of air-sealing on the cost of an ASHP would be smaller than that for a GSHP because an ASHP is cheaper than a GSHP. On the other hand, a GSHP consumes considerably less electricity than an ASHP for meeting the heating and cooling demands of buildings. The ASHP can thus reduce or avoid the need of upgrading electricity panels in SFHs for electrifying heating. The avoided cost for the electric panel upgrade would have improved the economic viability of the GSHP if it were accounted for in the economic analysis of this study. Further studies are recommended to investigate the economic viability of combining building efficiency measures (e.g., air-sealing, thermal insulation, and window upgradation) with an ASHP and GSHP.

5. Conclusions

This study investigated the impacts of air-sealing on the required capacity and cost of GSHP systems for electrifying typical SFHs in the US. Results from this study showed that combining air-sealing with GSHP deployment could increase energy savings and reduce the size of the GSHP system compared with just replacing the existing HVAC system with a GSHP. The benefits of air-sealing are more predominant in regions with cold or mild weather than in regions with a hot climate because of the larger temperature difference between indoor air and OA in colder regions in winter.

Reducing OA filtration from 0.8 to 0.35 ACH by air-sealing can cut electricity use for space heating by more than 30 % in all CZs (the highest reduction was 44 % in CZ 5A), and it will also shed 10%–25 % electricity usage for space cooling in hot climates (1A through 3B). However, in regions with moderate or cold climates, reducing OA infiltration increased cooling electricity usage. The GSHP's size can be reduced by 19%–48 % depending on CZs (with the largest reduction in CZs 5A and 7). Borehole drilling can be shortened by at least 12 % in all CZs and had a larger reduction (38%–73 %) in CZs with mild or cold climates (4C through 8). More energy savings and a reduction in GSHP size can be achieved by making the building airtight and supplying the required OA with a DOAS. In cold climates (6A, 6B, 7, and 8), compared with the GSHP system needed for meeting the thermal loads of leaky SFHs (with 0.8 ACH OA infiltration), the required GSHP capacity was reduced by 58%–70 %, the total borehole length was shortened by 27%–37 %, and the electricity use for space heating was lowered by 60%–67 %.

Through an economic analysis, this study found that GSHP (even with air-sealing) is not an economically viable solution in regions with very hot climates. However, in regions with mild and cold weather (3C through 8), combining air-sealing with GSHP is more cost effective than ASHP with or without the ITC. The ITC makes a GSHP economically viable in these regions even without air-sealing.

CRediT authorship contribution statement

Jyothis Anand: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaobing Liu:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Fady Anees:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Yanfei Li:** Writing – original draft, Software, Methodology. **Bill Eckman:** Writing – review & editing, Writing – original draft. **Mini Malhotra:** Writing – review & editing, Validation, Supervision, Resources, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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