IGSHPA Research Conference
Montréal, May 28-30, 2024

The role of air sealing while ground source heat pump system retrofits in the U.S. single-family houses

Jyothis Anand **Xiaobing Liu** **Yanfei Li** **Mini Malhotra**

ABSTRACT

Widespread commercial adoption of ground source heat pumps (GSHP) is hindered by the relatively high initial cost associated with drilling boreholes in the ground to deploy ground heat exchangers. Reducing the energy demand of buildings has the potential to reduce the required borehole length and the associated drilling costs. In single-family residential buildings, air sealing can significantly lower heating energy usage, according to recent studies and reports. Thus, air sealing in conjunction with GSHP retrofits can lower the required GSHP system's capacity and borehole length to meet the thermal demands of the buildings. In order to understand the role of combining air sealing with GSHP retrofit quantitatively, the current study employs a whole building energy simulation tool integrated with an advanced design tool for the ground heat exchanger to determine changes in required GSHP capacity, total borehole length, and building energy consumption for with- and without-air sealing in single-family houses in 3 climate zones in the United States. The study considers one representative city for each climate zone, Phoenix, AZ for a hot climate, Seattle, WA for a moderate climate, and Minneapolis, MN for a cold climate. The results from this study show that reducing air infiltration from 0.8 ACH to the minimum ventilation requirement (0.35 ACH) can reduce borehole length requirement by up to 24% in Phoenix, 32% in Seattle, and 70% in Minneapolis. A similar magnitude of reduction can be seen for GSHP capacity and total building energy usage as well.

INTRODUCTION

The United States administration has established a goal to become carbon neutral by 2050 and to cut greenhouse gas emissions by 50% by 2030 compared to 2005 levels (Kerry, 2022). The most popular kind of electric-driven heat pump available to replace fossil fuel-based heating sources is the air-source heat pump (ASHP). When an ASHP is in operation, its efficiency and capacity for heating and cooling are dependent upon the condition of outdoor air. Because of this, electric resistance heaters are typically installed in ASHPs to provide supplementary heating in situations where the outdoor air temperature is low and there is a high demand for heating. However, this can lead to large power draws when the electric resistance is engaged. Recent studies (Mai et al., 2018; Tarroja et al., 2018; White & Rhodes, 2019), indicated that the residential sector's switch from gas-fired furnaces to ASHPs would increase yearly electricity consumption and cause the peak demand for electricity to move from summer to winter. This change might have a significant impact on how the power grid functions, necessitating large new expenditures in the infrastructure of electric power generation and transmission. For example, according to a recent analysis, a fully electrified approach (using ASHP) may necessitate a 70% increase in the required capacity of the country's electrical infrastructure (Waite & Modi, 2020). Adopting ground source heat pump (GSHP) technology is one feasible answer for handling this problem.

However, the initial high cost of GSHP installation, mostly caused by drilling boreholes for installing ground heat exchangers (GHE) in the ground, prevents GSHP from being widely adopted. Reducing a building's energy demand for heating and cooling through envelope improvements can help reduce the thermal loads, and consequently, the initial cost of a GSHP system by reducing the required size of the heat pump and the GHE. Since infiltration contributes significantly to heating and cooling loads (Sawyer, 2014), it can significantly influence the required capacity of the GSHP system (thereby affecting the required total borehole length) as well as energy utilization. By caulking small cracks and gaps in the building's exterior, air leakage in single-family houses (SFHs) can be reduced by an average of 25–30%, reducing heat from escaping or entering the building (Tonn et al., 2011). Additional reduction in air leakage can be achieved by other envelope improvements such as adding insulation and upgrading windows (Younes et al., 2011).

Jyothis Anand is Post-Doctoral Research Associate, Yanfei Li & Mini Malhotra are R&D staffs, and Xiaobing Liu is a Group Leader at Oak Ridge National Laboratory, Oak Ridge, TN

Therefore, reducing the infiltration of buildings has the potential to lower the installed cost and the operation cost of GSHP systems. The winter peak electricity consumption brought on by buildings' electrification of space heating can also be decreased by the reduced size of GSHP systems.

Unfortunately, the impact of air-sealing SFHs on electrifying residential space heating with GSHPs has not been examined in prior research. The current study evaluates the costs and advantages of combining air sealing with GSHPs for retrofitting existing SFHs in various US climate zones as a first step in this direction. This study employs a whole building energy simulation tool integrated with an advanced design tool for GHE to determine changes in required capacity, total borehole length, and building energy consumption of the GSHP system resulting from air sealing and dedicated outdoor air ventilation in SFHs across 3 climate zones in the United States. It is important to note that the geological conditions play a major role in the sizing and performance of GSHP systems. Our study accounts for the difference in the undisturbed ground temperature at the three locations. We could expand our study in the future to evaluate the impact of air infiltration on the GSHP system under different geological conditions (e.g., with high or low ground thermal conductivity value).

METHODOLOGY

EnergyPlus (Crawley et al., 2001), a whole building energy modeling program, is used in this study to calculate the required GSHP system capacity and electricity consumption for meeting the annual heating and cooling demands of SFHs. EnergyPlus is an open-source platform developed by the U.S. Department of Energy's Building Technologies Office, as part of their building energy modeling program portfolio (Crawley et al., 2001). The US Department of Energy's residential prototype building models of a single-family detached house are used in this study (Mendon & Taylor, 2014). These models are variations of a 220.82 m^2 two-story house that is built to meet the requirements of energy standards. The prototype models following the 2006 Edition of IECC (International Energy Conservation Code) at 3 US climate zones are used in this study to represent existing SFHs (Mendon & Taylor, 2014). These models use ASHP and slab-on-grade foundations. The third edition of the typical meteorological year (TMY3) file of representative cities of the three climate zones is used to run simulations of the prototype models. For each prototype building model, 3 scenarios with the GSHP system were modeled with different air infiltration levels. Each GSHP scenario was modeled following a three-step process. The first step is to conduct an initial simulation using EnergyPlus to estimate the hourly thermal loads of GHE. Default values are used in this step for response factors of vertical borehole GHE (i.e., the g-functions (Spitler et al., 2021)), and borehole design parameters. The second step employs a new design tool of GHE, GHEdesigner (Mitchell et al., 2023), to determine the required borehole length and calculate the associated response factors based on the computed GHE hourly load. In the final step, whole-building energy simulation was performed again to predict building energy usage using the results from GHEdesigner.

The 3 scenarios of outdoor air (OA) infiltration modeled in this study include:

1. Leaky/High infiltration: Base case infiltration of 0.8 air change per hour (ACH), representing a typical residential construction (Margaret et al., 2022).
2. Low Infiltration: Infiltration reduced to 0.35 ACH, representing a retrofitted house while maintaining minimum indoor air quality without the need for ventilation (Stevens et al., 2013).
3. 0.03 ACH or negligible infiltration and dedicated outdoor air system (DOAS), representing air-tight new construction.

For the 3 scenarios, the ASHP in the prototype model was replaced with a GSHP system that uses vertical borehole GHE. For the models representing air-tight new construction (3rd scenario), DOAS is incorporated to provide ventilation in compliance with ASHRAE Standard 62.2 (Clark et al., 2019). The rated heating and cooling coefficients of performance of the GSHP unit are 4.0 and 6.5, respectively. EnergyPlus auto-sizes the GSHP unit and simulates the operation of the GSHP system. The entering water temperature of the GSHP is the supply water temperature of the GHE, so the effect of GHE supply temperature on the GSHP efficiency is modeled in the simulations. The default vertical borehole GHE design parameters used in the simulation are listed in Table 1. Table 2 shows the undisturbed ground temperature (Xing et al., 2017), number of boreholes, and length of each borehole for all climate zones investigated in this study. The climatic information of selected cities can be seen in Table 3.

The prototype building model uses design day loads for sizing the HVAC systems. This method might not always size the HVAC equipment 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 hours, which is the maximum number recommended by ANSI/ASHRAE/IES Standard 90.1-2010's Performance Rating Method Reference Manual (Goel & Rosenberg, 2016). To ensure the total unmet hours in our study are always less than 300 hours, the auto-sized GSHP capacity is corrected whenever it is necessary.

$Area_{Leakage}$ calculated with Eq. 1 (Chan et al., 2013) is used as a parameter in the ELA method. The GHE design parameters and thermal load are used to determine the size of the GHE (i.e., the number of boreholes and depth of each borehole) using GHEDesigner (Mitchell et al., 2023). The details from Table 2 are used in all cases to estimate the thermal load from the ground to size the GHE. The obtained number of boreholes and borehole length are updated in the building model to perform the final simulation. After the final simulation of each scenario, the heating and cooling energy usage, the required capacity of the GSHP system, and the size of GHE are compared to evaluate the effect of OA infiltration. The process is repeated for three ELA options for all the three climate zones used in the study.

$$Area_{Leakage} = \frac{Area_{floor} \times N_{Leakage}}{1000 \times N_{floor}^{0.3}} \quad (1)$$

$N_{Leakage}$ is the desired ACH value; $Area_{floor}$ is the floor area, and N_{floor} is the number of floors.

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)	3,900
U-tube pipe thickness (m)	0.0024	Ground conductivity (W/m-k)	1.30
U-tube pipe outer diameter (m)	0.0267	Ground heat capacity (kJ/m^3-K)	2,347
U-Tube distance (m)	0.025	System 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)	1,770	Maximum GHE supply temp. (°C)	35
Grout conductivity (W/m-k)	1.298	Minimum GHE supply temp. (°C)	-3

Table 2. Initial parameters for EnergyPlus simulation

Representative cities	Undisturbed Ground Temperature (C)	GHE number	GHE depth (m)
Phoenix, AZ	25.6	6	71.8
Seattle, WA	13.1	4	50
Minneapolis, MN	9.1	6	50

Table 3. Climatic information of the selected cities

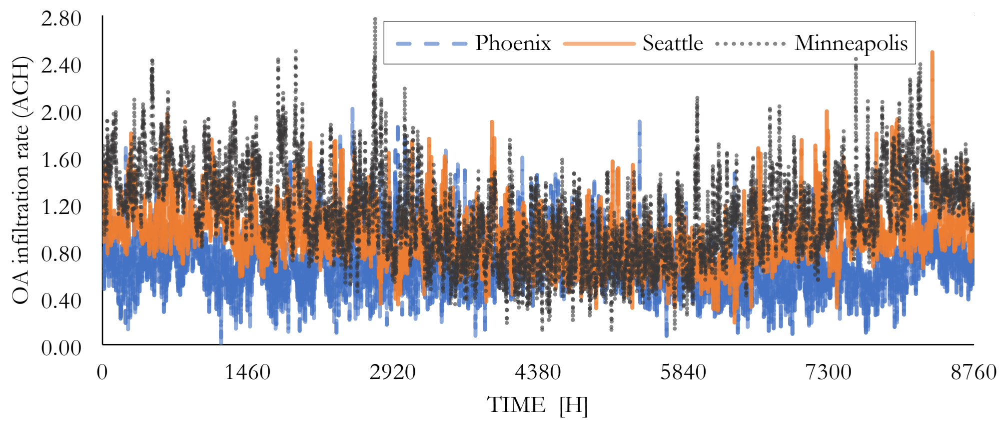
Representative cities	Köppen climate classification	Description
Phoenix, AZ	BWh	Hot desert climate
Seattle, WA	Csb	Warm-summer Mediterranean climate
Minneapolis, MN	Dfa	Hot-summer humid continental climate

RESULTS

Hourly outdoor air exchange rates

Figures 1 show the hourly outside air (OA) exchange rate in air change per hour (ACH) for high (0.8 ACH) and low (0.35 ACH) infiltration scenarios. Even though the study used the same ELA for each scenario in all 3 cities, as calculated using Eq. 1, the hourly OA infiltration rate varies at different locations depending on environmental factors, such as OA temperature and windspeed. Among the three cities considered in the study, Phoenix has the lowest wind speed and outdoor-indoor temperature difference, therefore, ACH is the lowest in Phoenix.

a)



b)

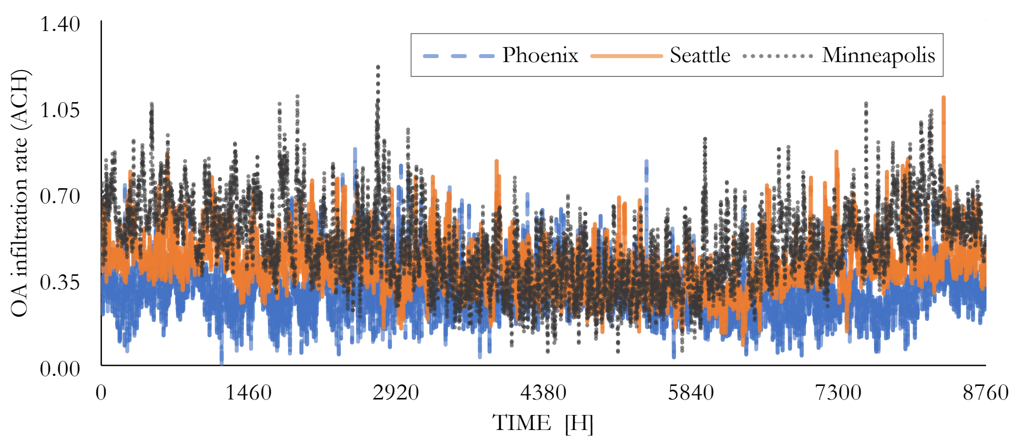


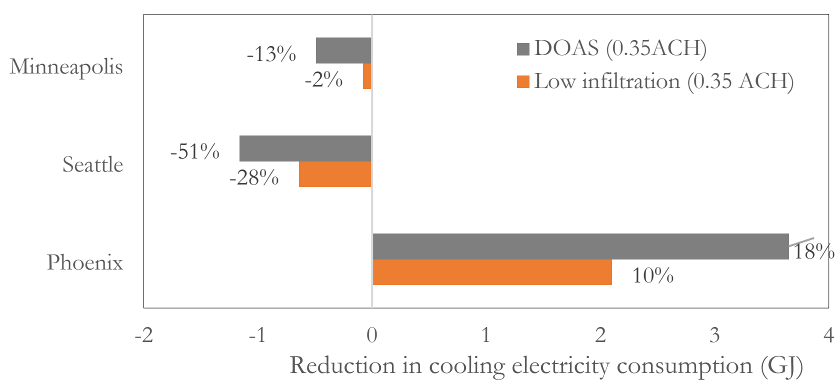
Figure 1. Hourly OA infiltration rate for a) High infiltration (0.8 ACH) and b) Low infiltration (0.35 ACH) SFHs modeled in this study.

The annual average OA infiltration rate of the modeled SHF in Phoenix is 0.3 ACH and 0.68 ACH for low and high infiltration scenarios, respectively. Minneapolis has the highest windspeed and outdoor-indoor temperature difference, therefore, its annual average OA infiltration rate is 0.48 ACH and 1.1 ACH for low and high infiltration scenarios, respectively. In the case of Seattle, these values are 0.40 ACH and 0.92 ACH for low and high infiltration scenarios, respectively. In contrast, the DOAS delivers OA at a constant 0.04342 m^3/s rate (which corresponds to 0.32 ACH). Together with the 0.03 ACH OA infiltration, the total OA ventilation rate is 0.35 ACH, which meets the minimum ventilation requirement recommended by ASHRAE 62.2 (2016). It is interesting to observe that the pattern of both graphs is the same, even though the magnitude of OA infiltration is almost doubled in the house with larger leakage areas, see Figure 1. The fluctuation of outdoor air conditions will be minimal for the SFHs with DOAS.

Impact of air sealing on GSHP energy usage

Figure 2 shows the reduction in cooling and heating electricity consumption of the GSHP system by reducing the infiltration rates from high infiltration (0.8 ACH), which is the average of existing SFHs in the US (Margaret et al., 2022), to low infiltration (0.35 ACH). Reducing OA infiltration results in a decrease in electricity consumption for space cooling in hot climate zones like Phoenix. However, in colder regions (e.g., Minneapolis), because OA temperature is relatively low in summer, especially in the evening, OA infiltration can help cool the building. Therefore, reducing OA infiltration will increase electricity consumption for cooling. It should be noted that, although cooling electricity consumption is increased in colder regions, the absolute value of cooling electricity consumption is small, as shown in Figure 2a. On the other hand, reducing OA infiltration always reduces the need for heating and the reduction is more significant in colder regions. It is interesting to observe in Figure 2b that although the percentages of heating electricity reduction are similar in Minneapolis and Seattle, the absolute value of heating electricity savings is doubled in Minneapolis (cold climate) when compared with that in Seattle (moderate climate) due to high heating demand in Minneapolis. In the case of Phoenix, even though the annual average OA infiltration rate in the Low infiltration scenario is lower than that of the DOAS scenario, the OA infiltration during peak cooling hours (when indoor-outdoor air temperature difference is high) in the Low infiltration scenario is higher than the constant OA rate delivered with the DOAS. Therefore, the controlled ventilation of DOAS results in lower cooling electricity consumption. Similarly, the controlled ventilation with DOAS saves more heating energy than just reducing air leakage (i.e., low infiltration scenario) at all three locations as shown in Figure 2b.

a)



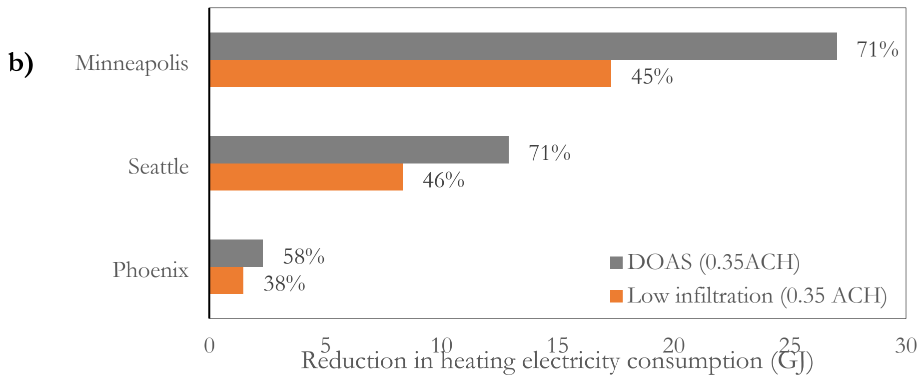


Figure 2. Reduction in a) cooling and b) heating electricity consumption by reducing infiltration from 0.8 ACH to 0.35 ACH (percentage reductions of electricity consumption for heating or cooling are shown as data labels).

Impact of air sealing on required capacity of GSHP system

Figure 3 shows the absolute values and reduction percentages of the required GSHP capacity by reducing OA infiltration. The required capacity of a GSHP system is determined by the maximum cooling/heating demand that the system needs to meet. Therefore, the role of air sealing will be dependent on the difference between OA temperature, indoor temperature setpoint, and wind speed at the peak period. As a result, for typical houses with high infiltration (0.8 ACH), their GSHP capacity needs to be higher in colder regions than in hotter regions. For instance, for Pheonix (hot region), the required capacity of GSHP is 10 kW, but for Minneapolis (cold region), the required capacity needs to be 21 kW to maintain the thermostat setpoint. However, for both low infiltration (0.35 ACH) and DOAS (0.35 ACH) scenarios, the GSHP system capacity needs to be higher in Phoenix, than that of Seattle and Minneapolis. This is because, once the OA infiltration is reduced, the heating demand reduces steeply than the cooling demand (as shown in Figure 2), which is determined mostly by the internal heat gain and solar radiation. Therefore, for SFHs with low infiltration, the cooling demand will play a more important role in deciding the required capacity of the GSHP system than the heating demand at the three cities investigated in this study. As a result, if the SFH is leaky (e.g., with 0.8 ACH OA infiltration), the required GSHP system capacity in the colder region (Minneapolis) is more than double that in the hot region (Pheonix), however, for SFHs with controlled ventilation to provide minimum allowed OA, the required GSHP system capacity in the cold region is 25% lower than that in a hot region.

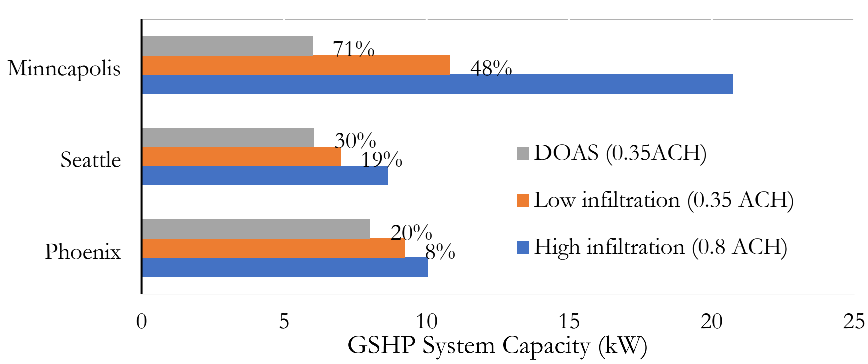


Figure 3. Required GSHP capacity resulting from various OA infiltration/ventilation levels (percentage reductions from 0.8 ACH are shown as data labels).

Impact of air sealing on required borehole length

Figure 4 shows the absolute values and percentage reduction of the required borehole length in various OA infiltration/ventilation scenarios. The results show that the required borehole length is in general longer in the hot region than in cold or moderate region (for the investigated cities in this study), mainly due to higher undisturbed ground temperature and the significantly imbalanced thermal loads (much more heat is rejected in the ground that extracted from the ground on annual basis) in Phoenix, as shown in Table 2. In this case, more borehole length is needed for transferring more heat to the ground within the design temperature range of the GHE (e.g., lower than 35℃). For the cold city (Minneapolis), the results show that the percentage reduction of heating electricity consumption and the required GSHP capacity and borehole length are similar (see Figures 2, 3, and 4) for both the DOAS scenario (~70%) and the low infiltration scenario (~45%). In the case of moderate climate (Seattle), we could observe a significant reduction in heating electricity usage from Figure 2b--71% reduction in the DOAS scenario and 45% reduction in the low infiltration scenario. But overall borehole length reduction is only between 30% to 35%, which is thought to be due to the increase in cooling needs, as shown in Figure 2a. In the case of hot city (Phoenix), the results showed a considerable reduction in the required borehole length in both the DOAS scenario (23%) and low infiltration scenario (18%).

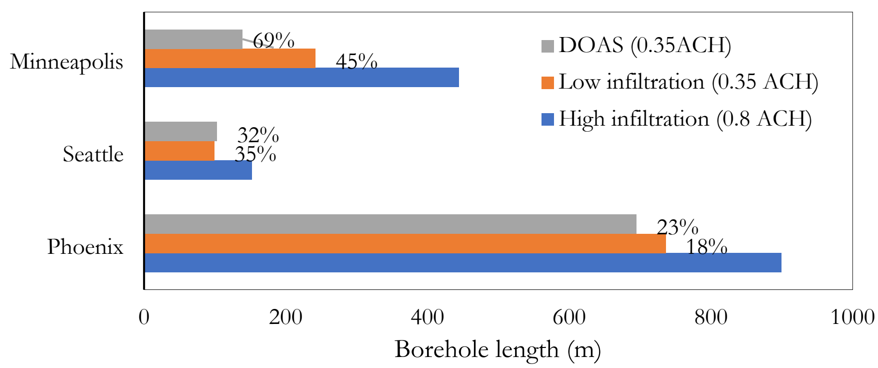


Figure 4. Required GHE borehole length while changing infiltration (percentage reductions from 0.8ACH are shown as data labels).

CONCLUSION

This study quantitively compared the benefits of combining air sealing with the GSHP system. The results from this study show that air sealing can reduce the required GSHP capacity and borehole length to meet the year-long heating and cooling demands of SFHs. In the case of space heating, reducing air infiltration can reduce electricity consumption in all three climate zones investigated in this study. For space cooling, reducing air sealing can reduce electricity consumption only in hot regions, in cold regions cooling electricity consumption will increase due to the reduced free cooling from OA infiltration. However, the magnitude of the increase in cooling electricity consumption in moderate and cold regions is significantly smaller than the savings in heating electricity consumption. Therefore, combining air sealing with a GSHP system can reduce electricity usage, the required GSHP capacity, and the required borehole length. The next step of this study is to conduct an economic analysis accounting for the initial cost of the GSHP unit, drilling cost, and lifecycle operating cost. This economic analysis is expected to answer whether combining air sealing will make the GSHP system more cost-effective.

ACKNOWLEDGMENTS

This manuscript is authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). This study is a part of an R&D project funded by the Geothermal Technologies Office of DOE. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the Department of Energy Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

REFERENCES

Chan, W. R., Joh, J., & Sherman, M. H. (2013). Analysis of air leakage measurements of US houses. *Energy and Buildings*, *66*, 616-625. https://doi.org/https://doi.org/10.1016/j.enbuild.2013.07.047

Clark, J. D., Less, B. D., Dutton, S. M., Walker, I. S., & Sherman, M. H. (2019). Efficacy of occupancy-based smart ventilation control strategies in energy-efficient homes in the United States. *Building and Environment*, *156*, 253-267.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., . . . Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 319-331. https://doi.org/https://doi.org/10.1016/S0378-7788(00)00114-6

Kerry, J. (2022). The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050.". *United States Department of State*.

Mai, T. T., Jadun, P., Logan, J. S., McMillan, C. A., Muratori, M., Steinberg, D. C., . . . Nelson, B. (2018). *Electrification futures study: Scenarios of electric technology adoption and power consumption for the United States*.

Margaret, P., Natalie Mims, F., Eric, W., Andrew, P., & Elaina, P. (2022). *End-Use Load Profiles for the U.S. Building Stock: Practical Guidance on Accessing and Using the Data*.

Mendon, V. V., & Taylor, Z. T. (2014). *Development of Residential Prototype Building Models and Analysis System for Large-Scale Energy Efficiency Studies Using EnergyPlus* ASHRAE/IBPSA-USA Building Simulation Conference, Atlanta, Georgia. https://www.osti.gov/biblio/1194327

Mitchell, M., Lee, E., Spitler, J., Borshon, I., Cook, J., Liu, X., & West, T. (2023). *GHEDesigner [SWR-23-33]*.

Sawyer, K. (2014). Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. *US Department of Energy: Washington, DC, USA*.

Spitler, J., Cook, J., West, T., & Liu, X. (2021). *G-Function Library for Modeling Vertical Bore Ground Heat Exchanger*.

Stevens, D. T., Francisco, P., Emmerich, S. J., Baylon, D. A., Brennan, T. M., Crawford, R. R., . . . Fairey, P. W. (2013). ANSI/ASHRAE Standard 62.2-2013-Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings ASHRAE. *ASHRAE: Atlanta, GA, USA*, 58.

Tarroja, B., Chiang, F., AghaKouchak, A., Samuelsen, S., Raghavan, S. V., Wei, M., . . . Hong, T. (2018). Translating climate change and heating system electrification impacts on building energy use to future greenhouse gas emissions and electric grid capacity requirements in California. *Applied energy*, *225*, 522-534.

Tonn, B., Rose, E., Schmoyer, R., Eisenberg, J., Ternes, M., Schweitzer, M., & Hendrick, T. (2011). Evaluation of the National Weatherization Assistance Program during Program Years 2009-2011 (American Reinvestment and Recovery Act Period). *ORNL/TM-2011/87. Oak Ridge, TN: Oak Ridge National Laboratory*.

Waite, M., & Modi, V. (2020). Electricity load implications of space heating decarbonization pathways. *Joule*, *4*(2), 376-394.

White, P. M., & Rhodes, J. D. (2019). Electrification of heating in the Texas residential sector. *Technical Report IdeaSmiths, LL C.*

Xing, L., Spitler, J. D., & Bandyopadhyay, A. (2017). Prediction of undisturbed ground temperature using analytical and numerical modeling. Part III: Experimental validation of a world-wide dataset. *Science and Technology for the Built Environment*, *23*(5), 826-842.

Younes, C., Shdid, C. A., & Bitsuamlak, G. (2011). Air infiltration through building envelopes: A review. *Journal of Building Physics*, *35*(3), 267-302. https://doi.org/10.1177/1744259111423085