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# Impact Analysis of Heating Electrification in US Buildings with Geothermal Heat Pumps

**Xiaobing Liu** **Xiaofei Wang**

**Mini Malhotra** **Jonathan Ho**

**Yanfei Li**

**Jamie Lian**

## ABSTRACT

*Few studies have investigated the impacts of large-scale deployment of geothermal heat pumps (GHPs, also called ground source heat pumps) on the electric grid. GHPs utilize the ground as a heat source to warm buildings more efficiently than other space-heating systems. The coupling with the ground offers seasonal thermal storage so that GHPs can also cool buildings in summer more efficiently than other space-cooling systems. This study simulated the performance of GHP systems for various commercial and residential buildings in 15 climate zones in the United States. Combined with the latest End-Use Load Profiles of the US building stock and grid modeling, this study aims to assess the impacts of a national deployment of GHP systems on the US electric grid in terms of energy consumption, emissions, and operational resilience. The preliminary results show that the GHP deployment can save 429 billion kWh of electricity (a 19% reduction from baseline) and reduce carbon emissions by 496 million tons per year (a 31 % reduction from baseline). A geographical view of the results indicates that retrofitting existing HVAC systems with new GHP systems can lead to further reductions in annual electricity consumption and peak electricity demand in the southern regions of the United States than in other parts of the country. On the other hand, GHP retrofits result in higher percentages of site energy savings and carbon emission reduction in the north (cold climates) than in the south (warm climates).*

## INTRODUCTION

In the United States, the building sector (including residential and commercial buildings) consumes 40% of primary energy and accounts for 75% of electricity use, which contributes to 35% of carbon emissions in the United States (EIA 2020). The US administration has set a target to reduce greenhouse gas emissions by 50% by 2030 and to become a carbon-neutral economy by 2050 (Kerry 2022). The administration also set a goal to achieve 100% clean electricity by 2035. Using heat pumps to replace fossil-fuel furnaces has become a trend in the building sector to achieve decarbonization. Mai et al. (2018), Tarroja et al. (2018), and White and Rhodes (2019) indicate that using air-source heat pumps to replace gas-fired furnaces in the residential sector would result in higher annual electricity consumption and a shift in electric peak demand from summer to winter, and this shift would be a substantial change in how the grid operates and would require substantial new investments in electric power infrastructure.

Xiaobing Liu (liux2@ornl.gov) and Mini Malhotra are R&D Staff at Oak Ridge National Laboratory (ORNL). Yanfei Li is an associate R&D staff at ORNL. Jamie Lian is the group leader at ORNL. Xiaofei Wang is a PhD student from the University of Tennessee, Knoxville. Jonathan Ho is an energy analyst at the National Renewable Energy Laboratory.

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Previous studies (e.g., Bayer et al. 2012, Yuan et al. 2012, You et al. 2021) have reported that geothermal heat pumps (GHPs, also called ground source heat pumps) are more energy-efficient than conventional heating and cooling systems. GHPs achieve this efficiency by utilizing the ground, which has a stable temperature year-round, as a heat source for heating operation and a heat sink for cooling operation. When driven with renewable power, GHPs do not result in any emissions. Liu et al. (2015) reported that by 2012 the cumulative capacity of GHPs installed in the United States had reached 3.9 million refrigeration tons. The US Department of Energy's (DOE's) GeoVision study (2019) predicted that the "equivalent of more than 28 million households [would be] using geothermal heat pumps by 2050." Previous studies (Trumpy et al. 2016 and Liu et al. 2019) estimated the potential energy savings and emission reductions of retrofitting US buildings with GHPs, but few studies have investigated the impacts of large-scale deployment of GHPs on the electric grid.

The contiguous US electric power system can be divided into 134 balance areas (BAs) for modeling purposes, as shown in Figure 1. Each BA represents the topology of the contiguous US electric power system. These regions are delineated by counties and represent the spatial resolution at which generation, load, and transmission are balanced in the grid model. The boundaries of the balancing areas align with the boundaries of the county groups.

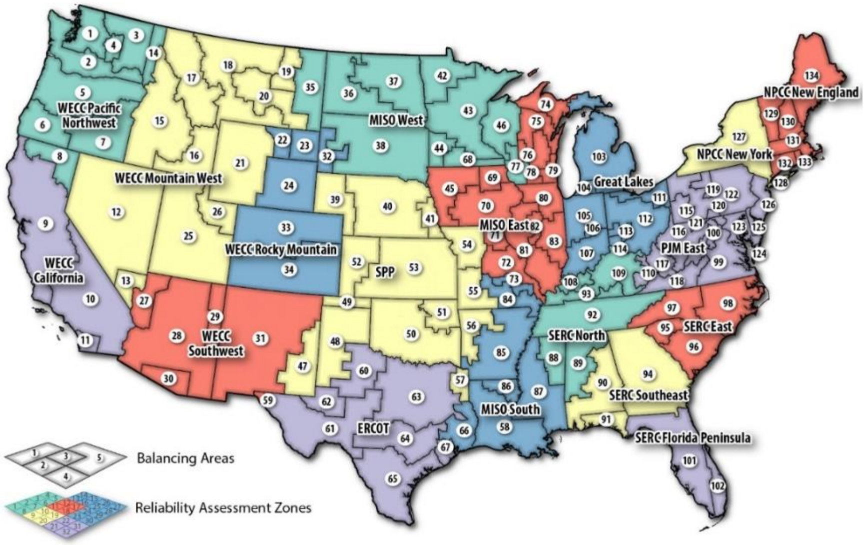

**Figure 1** BAs of the contiguous US electric power system considered in this study.

This paper introduces the methodology and data sources used to evaluate the impacts on energy consumption and carbon emissions that would result from a mass deployment of GHP in the United States. The results of this analysis are presented for each BA of the contiguous US electric power system. Additionally, a geospatial representation of energy savings and emission reductions across the United States is presented.

## METHODOLOGY

The procedure for analyzing the impacts of mass GHP deployment on the US grids includes two steps. In the first step, the impacts of GHP retrofits on the energy consumption and electricity demand of residential and commercial building stocks were quantified for each BA and aggregated across the contiguous United States (i.e., excluding Alaska and Hawaii). In the second step, the difference in hourly electricity use that resulted from the GHP retrofits is used as an input in the grid modeling. The grid modeling is ongoing as of this writing, and the results will be reported in a future paper. Existing buildings have diverse characteristics and operation schedules that must be considered when calculating the end-use load profile (EULP) of existing building stocks. This study uses the EULP dataset published by the National Renewable Energy Laboratory (2021) for US building stock as the baseline for assessing the impacts of GHP retrofits. New EULPs that result from retrofitting all applicable buildings in the United States with new GHP systems were calculated with the following procedure (as shown in Figure 2):

1. Replace existing HVAC systems in the prototype models with new distributed GHP systems.

These prototype models include 16 commercial building types (e.g., office, school, retail, restaurant, hotel, hospital, warehouse) and 4 single-family house types, each with different space-heating systems (gas/oil furnace, electric resistance, or air-source heat pump). These prototype models represent typical US buildings (US DOE 2022) in 15 climate zones in the United States (ASHRAE 2013).

Distributed GHP systems are commonly used in the United States, and they provide independent climate control in each thermal zone of the building without using supplemental heating or cooling. The GHP unit's rated coefficients of performance (COP) are 4.0 for heating and 6.5 for cooling. A vertical bore ground heat exchanger (VBGHE)[1] is sized to maintain the leaving fluid temperature of the VBGHE between 1°C and 35°C year-round. Outdoor air is provided with a dedicated ventilation system in parallel with the distributed GHP system.

2. Predict energy consumption of the retrofitted building by using an integrated GHP simulation program developed at DOE's Oak Ridge National Laboratory (ORNL) (Liu et al. 2022).

The program accounts for energy savings from the GHP system's higher operational efficiency; from avoiding simultaneous heating and cooling, which is common in the conventional variable air volume systems; and from the reduced fan power use owing to a dedicated outdoor air ventilation system and improved fan control and efficiency.

3. Calculate hourly relative differences (faction factors) in the HVAC-related site energy consumption between the existing HVAC system and a new GHP system for each prototype building in the 15 climate zones.

4. Identify valid candidates for GHP retrofits by using the metadata summary of the characteristics of the residential and commercial building stock in the latest EULP database.

This process excludes buildings that use district heating/cooling (i.e., no energy consumption for heating/cooling at the building), mobile homes, buildings without heating/cooling, and buildings that already use GHPs.

5. Apply the fraction factors to the EULPs of existing buildings (i.e., baseline) that are valid candidates for GHP retrofits to determine the new EULPs that result from the GHP retrofit.[2]

6. Aggregate the baseline and new EULPs by county and by BA to calculate changes in hourly electricity consumption, the annual peak electricity demand, and fossil fuel use in each BA.

7. Calculate the resulting carbon-emission reduction in each BA by using the 2021 Cambium data for Long-run Marginal Emission Rates for Electricity (Gagnon, Hale, and Cole 2022) and ASHRAE Standard 105-2021 for carbon emission factors of various fossil fuels (ASHRAE 2022).

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[1] Boreholes are laid out in a square of a near-square field with 6.1 m (20 ft) bore spacing.

[2] This may result in some misalignment between the thermal demands and the faction factors for some buildings in shoulder seasons.

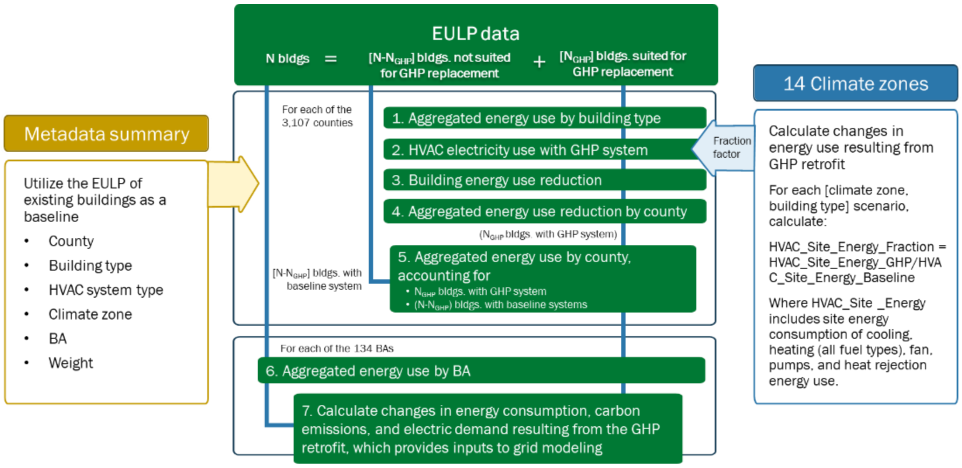


**Figure 2** Flowchart of impact analysis for energy consumption and carbon emissions.

## RESULTS AND ANALYSIS

Results from the study indicate that retrofitting all applicable buildings in the United States with GHPs can reduce electricity usage by 429 billion kWh (a 19% reduction from the baseline EULP) each year. It will also eliminate 4,920 billion MJ of annual fossil fuel (e.g., natural gas, heating oil, propane) consumption. As a combined result of the reduced electricity and fossil fuel consumption, 496 million MT of carbon emissions will be avoided (a 36% reduction from baseline) each year. The impacts on energy consumption in each BA and the geospatial characterization of the energy savings and emission reduction are presented below.

### GHP Impacts at Each BA

Table 1 lists the minimum, maximum, and average values of the changes in electricity and fossil fuel consumption as well as the carbon emissions that result from the GHP retrofits in the 134 BAs. The percentages of these changes are also shown. Positive values indicate savings or reduction compared with the baseline and reflect the benefits of GHP retrofits. Negative values indicate an increase in energy use or carbon emission. Most BAs show savings in electricity, and fossil fuel consumption and carbon emissions are reduced in all BAs. The GHP retrofits lead to increased electricity consumption in a few BAs in the northeastern United States because most space heating in these BAs is provided by furnaces or boilers that consume fossil fuels. Replacing these furnaces and boilers with GHPs will consume more electricity but will eliminate fossil fuel consumption for space heating. Propane and heating oil are not used in all BAs. In BAs without propane or heating oil consumption, the change in propane or heating oil consumption is zero. The large negative value in the percentage of peak electricity demand reduction is in a BA for which cooling demand is low, but heating demand is high, and the existing heating systems are gas furnaces. Therefore, GHP retrofits result in a peak electric demand in winter that is higher than the previous peak electric demand, which occurred in summer.

**Table 1. Changes in Energy Consumption from GHP Retrofits in all BAs**

| Energy Consumption Items | Min | Max | Mean |
|---|---|---|---|
| Electricity Savings [TWh = $10^9$ KWh] | -0.2 | 28.0 | 3.2 |
| Percentage of Electricity Savings [%] | -2.1 | 65.9 | 20.2 |
| Peak Electricity Demand Reduction [GW = $10^6$ KW] | -0.1 | 11.9 | 1.5 |
| Percentage of Peak Electricity Demand Reduction [%] | -68.4 | 75.2 | 32.9 |
| Natural Gas Savings [PJ = $10^{15}$ J] | 0.0 | 405.0 | 29.9 |

|  |  |  |  |
|---|---|---|---|
| Percentage of Natural Gas Savings [%] | 1.4 | 82.3 | 62.4 |
| Heating Oil Savings [PJ = $10^{15}$ J] | 0.0 | 103.9 | 4.4 |
| Percentage of Heating Oil Savings [%] | 0.0 | 100.0 | 57.2 |
| Propane Savings [PJ = $10^{15}$ J] | 0.0 | 25.7 | 2.5 |
| Percentage of Propane Savings [%] | 0.0 | 90.1 | 61.5 |
| Carbon Reduction [Million MT = $10^9$ kg] | 0.003 | 3.8 | 0.37 |
| Percentage of Carbon Reductions [%] | 18.7 | 82.6 | 50.7 |

Figure 3 shows the changes in annual electricity consumption and peak electricity demand in each of the 134 BAs. The red bars represent the absolute values of the changes, and the blue dots indicate the percentages of the changes compared with baseline EULP. Electricity savings (positive values) are predicted for most BAs. More than 10 TWh of electricity can be saved each year in 15 BAs, which include populated areas. The annual peak electricity demand is also reduced significantly (around 30%) in these BAs. Figure 4 shows the annual savings in natural gas, heating oil, and propane in each BA, including the magnitude of savings and percentage of savings. In 9 BAs, more than 100 PJ of natural gas consumption can be avoided by performing GHP retrofits. Across all the BAs, the average natural gas savings is about 63%. Heating oil is used only in a small number of BAs in the northeastern United States, and the magnitude of savings is only about 25% of the natural gas savings. The magnitude of savings for propane is lower than that of natural gas and heating oil. However, propane is more widely used in various BAs than heating oil, and 8 BAs would have more than 8 PJ of propane savings each year. Figure 5 shows the magnitude and percentages of carbon emission reduction in each BA. More than 1.15 million MT of carbon emissions can be reduced in each of the 13 BAs that have more significant emission reduction than other BAs by replacing existing HVAC systems with GHPs. On average, carbon emissions would be reduced by 50.7% in all BAs.

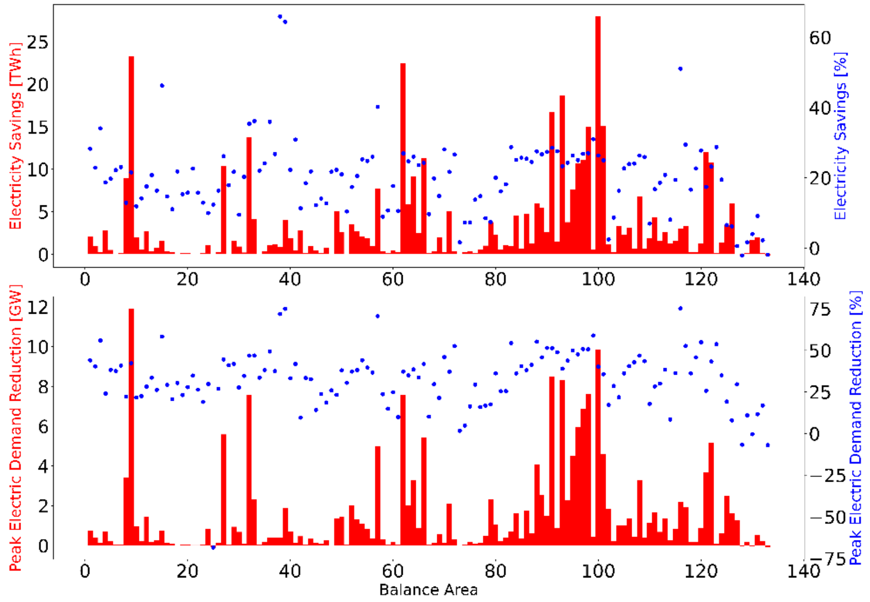


**Figure 3** Annual electricity savings and peak electric demand reduction in each of the 134 BAs after GHP retrofits.

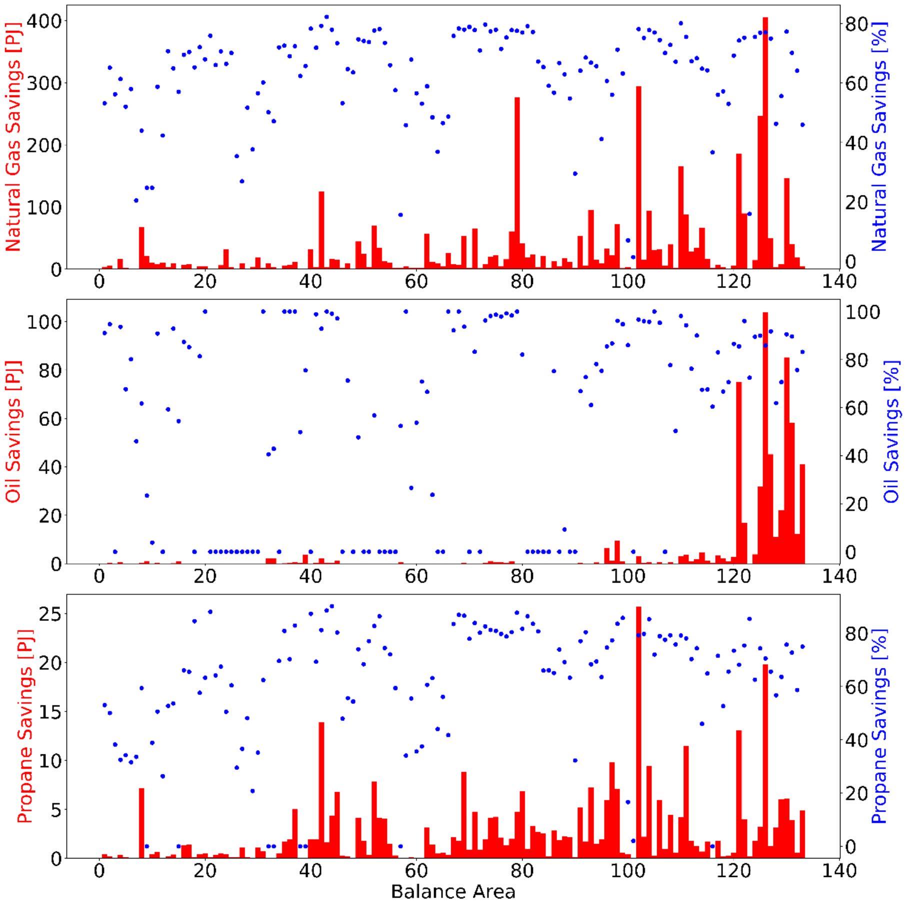


**Figure 4** Annual savings in fuel consumption in each of the 134 BAs after GHP retrofits.

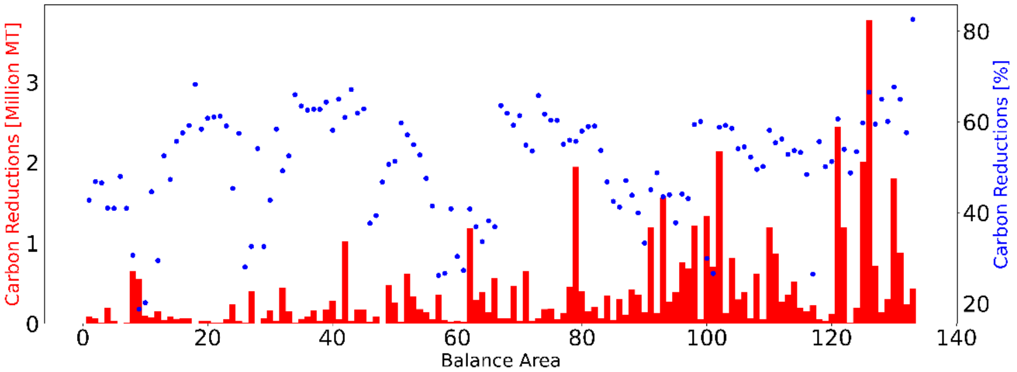
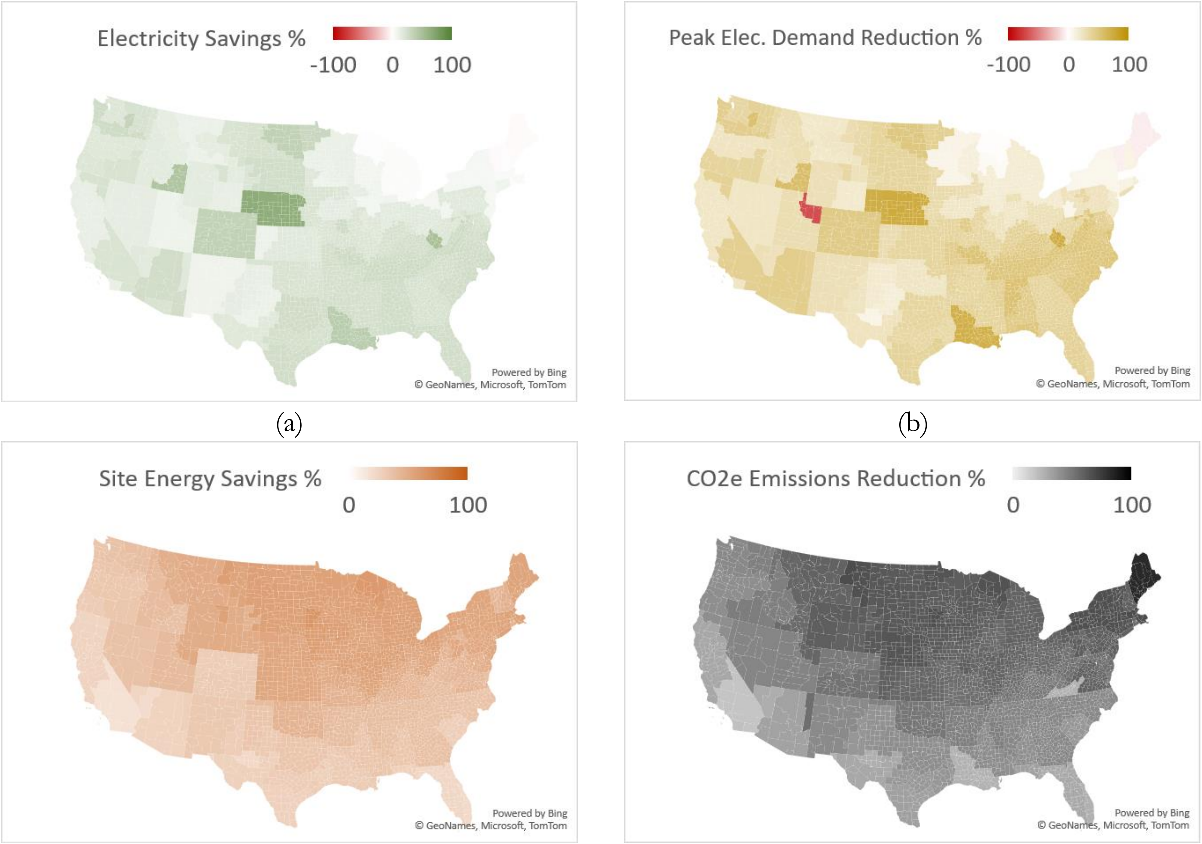


**Figure 5** Annual carbon emission reduction in each of the 134 BAs after GHP retrofits.

## Geospatial Characterization of the Impacts

Figure 6 provides a geospatial representation of the changes in annual electricity consumption, annual peak electric demand, site energy consumption, and carbon emissions that result from the mass deployment of GHPs in each BA. Figures 6(a) and 6(b) show that retrofitting the existing HVAC systems with new GHPs will reduce electricity consumption in most parts of the United States, except in a few BAs in the northeastern region. More significant reductions in annual electricity consumption and peak electric demand will be achieved in southern BAs. On the other hand, Figures 6(c) and 6(d) show that GHP retrofits result in higher percentages of site energy savings and carbon emission reduction in the northern BAs (colder climates) than in the southern BAs.

These regional differences are due to different heating and cooling demands in each BA and the energy sources used for providing space heating in the existing HVAC systems. According to EIA (2021), more than 99% of existing HVAC systems consume electricity to provide space cooling. GHPs will reduce electricity consumption for space cooling because they are more efficient than existing space cooling systems. Existing space heating systems use electricity or fossil fuels. If a GHP replaces an electric heating system (e.g., electric resistance or air-source heat pump), then it will further reduce electricity consumption. But if it replaces fuel-burning heating equipment, then it will eliminate fuel consumption while consuming some electricity. Therefore, in the southern BAs, where the cooling demand is higher and more than 40% of space heating is provided with electricity, the GHP retrofits will result in significant savings in electricity. In a contrast, because most space heating in the northern BAs is provided by fossil fuels, the GHP retrofits will result in increased electricity consumption in the heating season that will offset a part of the electricity savings obtained during the cooling season; in some situations, this may even increase annual electricity consumption. Therefore, electricity savings gained from GHP retrofits in the northern BAs are not as significant as in the southern BAs. Furthermore, the difference in energy efficiency between GHPs and conventional HVAC for cooling (e.g., a GHP with 6.5 cooling COP vs. a chiller with 5 cooling COP), which is determined based on the site energy consumption, is smaller than that for heating (e.g., a GHP with 4.0 heating COP vs. a natural gas furnace with 0.8 burner efficiency). Therefore, the site energy reduction would be higher in the northern BAs, where buildings have larger heating demands.



(a) (b)

(c) (d)

**Figure 6** Geospatial representation of the changes in (a) annual electricity consumption, (b) annual peak electric demand, (c) site energy consumption, and (d) carbon emissions that would result from the mass deployment of GHPs in each BA.

## CONCLUSIONS

This study assessed the impacts of the national deployment of GHP systems on the US electric grid in terms of energy consumption, peak demand, and carbon emissions. To accomplish this task, the EULP of residential and commercial buildings before and after the GHP retrofits were calculated and aggregated by BAs to represent the topology of the contiguous US electric grid. Carbon emission reductions associated with the GHP retrofits were also evaluated based on the latest information on the grid mix and emission factors of various fossil fuels.

The preliminary results of this study indicate that the national deployment of GHPs can save 429 billion kWh of electricity (a 19% reduction from baseline) annually and reduce 496 million tons of carbon emissions (a 31% reduction from baseline) each year. The GHPs in cold climates are more effective for reducing site energy consumption and carbon emissions. Higher electricity savings can be achieved in the southern BAs than in other parts of the United States, and peak electric demand reduction is highest in densely populated areas in the southern United States.

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## REFERENCES

ASHRAE. 2022. "ANSI/ASHRAE 105-2021 - Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions."

ASHRAE, ANSI. 2013. "Standard 169-2013, Climatic Data for Building Design Standards." *ASHRAE, Atlanta*.

Bayer, Peter, Dominik Saner, Stephan Bolay, Ladislaus Rybach, and Philipp Blum. 2012. "Greenhouse Gas Emission Savings of Ground Source Heat Pump Systems in Europe: A Review." *Renewable and Sustainable Energy Reviews* 16(2):1256–67.

EIA. 2020. "U.S. Energy-Related Carbon Dioxide Emissions 2020." Retrieved January 14, 2022 (https://www.eia.gov/environment/emissions/carbon/).

Gagnon, Pieter, Elaine Hale, and Wesley Cole. 2022. "Long-Run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data." 4 files.

Kerry, John. 2022. "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050."

Liu, Xiaobing, Jason DeGraw, M. Malhotra, N. Kunwar, W. Forman, M. Adams, G. Accawi, B. Brass, and Joshua New. 2022. "Development of a Web-Based GSHP Screening Tool." Las Vegas, NV.

Liu, Xiaobing, Shilei Lu, Patrick Hughes, and Zhe Cai. 2015. "A Comparative Study of the Status of GSHP Applications in the United States and China." *Renewable and Sustainable Energy Reviews* 48:558–70. doi: 10.1016/j.rser.2015.04.035.

Luo, Jin, Joachim Rohn, Wei Xiang, David Bertermann, and Philipp Blum. 2016. "A Review of Ground Investigations for Ground Source Heat Pump (GSHP) Systems." *Energy and Buildings* 117:160–75.

Mai, Trieu T., Paige Jadun, Jeffrey S. Logan, Colin A. McMillan, Matteo Muratori, Daniel C. Steinberg, Laura J. Vimmerstedt, Benjamin Haley, Ryan Jones, and Brent Nelson. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*. National Renewable Energy Lab. (NREL), Golden, CO (United States).

Tarroja, Brian, Felicia Chiang, Amir AghaKouchak, Scott Samuelsen, Shuba V. Raghavan, Max Wei, Kaiyu Sun, and Tianzhen Hong. 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* 225:522–34.

White, Philip M., and Joshua D. Rhodes. 2019. "Electrification of Heating in the Texas Residential Sector." *Technical Report IdeaSmiths, LL C.*

You, Tian, Wei Wu, Hongxing Yang, Jiankun Liu, and Xianting Li. 2021. "Hybrid Photovoltaic/Thermal and Ground Source Heat Pump: Review and Perspective." *Renewable and Sustainable Energy Reviews* 151:111569.

Yuan, Yanping, Xiaoling Cao, Liangliang Sun, Bo Lei, and Nanyang Yu. 2012. "Ground Source Heat Pump System: A Review of Simulation in China." *Renewable and Sustainable Energy Reviews* 16(9):6814–22.