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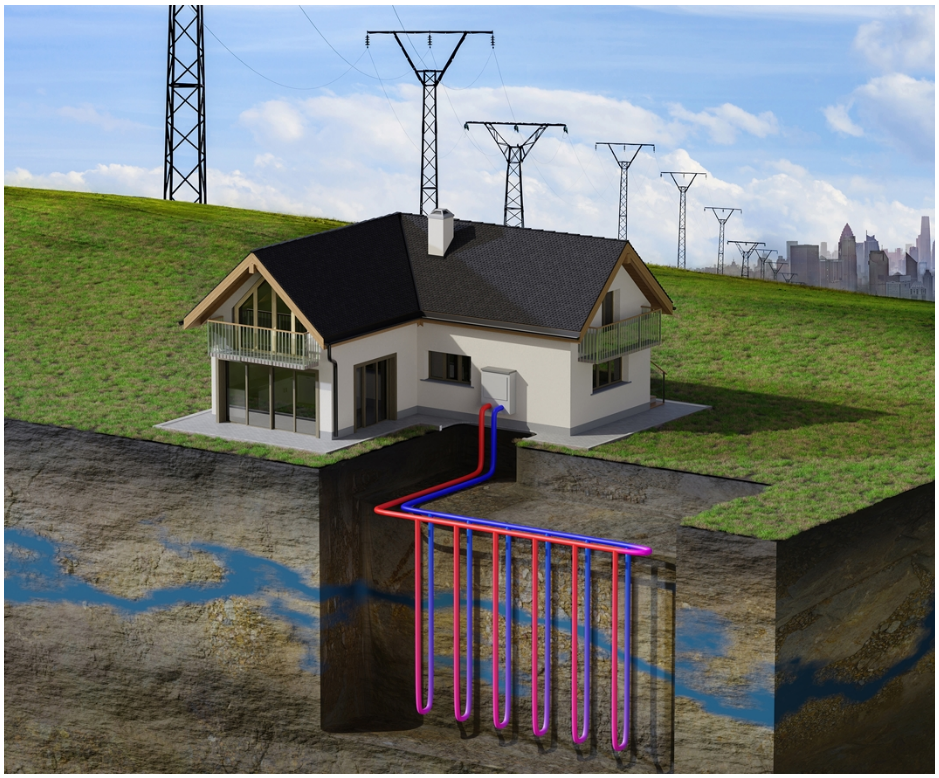

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November 2023

OAK RIDGE National Laboratory

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Energy Science and Technology Directorate

GRID COST AND TOTAL EMISSIONS REDUCTIONS THROUGH MASS DEPLOYMENT OF GEOTHERMAL HEAT PUMPS FOR BUILDING HEATING AND COOLING ELECTRIFICATION IN THE UNITED STATES

Xiaobing Liu
Jonathan Ho*
Jeff Winick♦
Sean Porse♦
Jamie Lian
Xiaofei Wang†
Weijia Liu*
Mini Malhotra
Yanfei Li
Jyothis Anand

* National Renewable Energy Laboratory
♦ US Department of Energy
† Joint position at Oak Ridge National Laboratory and the University of Tennessee, Knoxville

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
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ABBREVIATIONS

AEO	Annual Energy Outlook
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ANSI	American National Standards Institute
ASHP	air source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	balancing area
CEM	capacity expansion modeling
CO_2e	CO_2 equivalent
COP	coefficient of performance
CSP	concentrating solar power
CZ	climate zone
DOAS	dedicated outdoor air system
DOE	US Department of Energy
DX	direct expansion
EER	energy efficiency ratio
EFS	*Electrification Futures Study*
ERCOT	Electric Reliability Council of Texas
EULP	end-use load profile
GHE	ground heat exchanger
GHG	greenhouse gas
GHP	geothermal heat pump
H_2-CT	hydrogen combustion turbine
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
ISO	International Organization for Standardization
LMP	locational marginal price
MLP	multilayer perceptron
MMT	million metric tons
NERC	North American Electric Reliability Corporation
NG-CC	natural gas combined cycle
NG-CT	natural gas combustion turbine
NPCC	Northeast Power Coordinating Council
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OA	outdoor air
ORNL	Oak Ridge National Laboratory
PCM	production cost modeling
PSH	pumped storage hydropower
PTAC	packaged terminal air-conditioner
PV	photovoltaic
RAZ	reliability assessment zone
ReEDS	Regional Energy Deployment System Model
SEER	seasonal energy efficiency ratio
SERC	SERC Reliability Corporation
SFH	single-family home
TMY3	third edition of typical meteorological year data
VBGHE	vertical bore ground heat exchanger
VRE	variable renewable energy

NOMENCLATURE

Item	Definition and explanation
Annual load (TWh)	Total electrical energy consumption at the point of use, including end-use demand and storage charging but not including losses between the points of generation and the points of use
Annual generation (TWh)	Total electrical energy generation, which is the sum of the loads at the points of use (including storage charging) plus the losses in delivering energy from the point of generation to the loads
Annual generation cost ($ billion)	Total electricity generation operational costs, including fuel and variable operation and maintenance cost
Annual generator revenue ($ billion)	Total payment for electrical energy in the wholesale market; equivalent to the sum of the product of locational marginal price and demand at each region
Average wholesale electricity price ($/MWh)	Average wholesale price that utilities paid for electricity to serve the annual load
Annual operating reserve provision (TWh)	Total hourly reserve capacity throughout the year
Annual unserved load (GWh)	Total unserved load, possibly because of maintenance, congestion, and so on
Annual peak demand (GW)	Peak demand throughout the year
RA eligible capacity (GW)	The portion of a generator or storage capacity that can be reliably counted on during a period of need ensuring resource adequacy
Generation capacity (GW)	The summation of all power plant nameplate capacities. The capacity of all plants is not always available (e.g., solar capacity at night, or when a power plant is in maintenance or shutdown). In this study, *generation capacity* also includes battery power capacity.
Battery capacity (GW)	The summation of the maximum amount of power that can be delivered by the batteries
Battery energy storage (GWh)	Total energy that can be stored in the battery
Emissions (MT or MMT)	Emissions of CH_4, CO_2, NO_x, and/or SO_2 that are released as the products of the combustion of fossil fuels at power plants or in buildings for space heating. Emissions from water heating for use in buildings were not evaluated in this study.
Annual fuel cost ($ billion)	Total generation cost associated with fuel consumption
Annual fuel offtake (TJ)	Total fuel energy (i.e., heat value) consumed for generation
Net demand (TW)	Electric demand minus renewable power generation
EULP	End-use load profile, which includes hourly electric and fuel consumption in an individual building or a cluster of buildings

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EXECUTIVE SUMMARY

This report presents the results of a study on the potential grid impacts of national-scale mass deployment of geothermal heat pumps (GHPs) coupled with weatherization in single-family homes (SFHs) from 2022 to 2050. GHPs are a technology readiness level 10, commercially available technology across the United States. This study is an impact analysis only; installed costs and available land areas for installing GHPs are not accounted for in determining their estimated deployment. The three scenarios studied were (1) continuing to operate the grid as it is today (the *Base scenario*), (2) a scenario to reach 95% grid emissions reductions by 2035 and 100% clean electricity by 2050 (the *Grid Decarbonization scenario*), and (3) a scenario in which the Grid Decarbonization scenario is expanded to include the electrification of wide portions of the economy, including building heating (the *Electrification Futures Study* or *EFS scenario*). The analysis team modeled each of these three scenarios with and without GHP deployment to a large percentage of US building floor space.[1] In all cases, deployment of approximately 5 million GHPs per year demonstrated system cost savings on the grid, consumer fuel cost savings through eliminated fuel combustion for space heating, and CO_2 emission reductions from avoided on-site fuel combustion—and, in the case of the Base scenario, CO_2 emissions reductions from the electric power sector.[2]

GHPs have traditionally been viewed as a building energy technology. The most notable result of this study, however, is the demonstration that GHPs coupled with weatherization in SFHs are primarily a grid-cost reduction tool and technology that, when deployed at a national scale, also substantially reduces CO_2 emissions, even in the absence of any other decarbonization policy.

Key Findings

GHPs widely deployed across the United States could result in the following key benefits.

1. Wholesale payments for electric grid services are reduced by at least $300 billion through 2050. This study evaluated the all-in electricity costs that are avoided by GHP deployment. Savings are 10% ($316 billion) in the Base scenario, 13% ($557 billion) in the Grid Decarbonization scenario, and 11% ($607 billion) in the EFS scenario. These reported numbers are the present-day value of future savings (at a 5% discount rate).
    a. For the Grid Decarbonization scenario, the undiscounted cumulative savings through 2050 are more than $1 trillion. This scenario has the effect of reducing the wholesale price of electricity by 12% (a $10/MWh price reduction).
    b. GHPs reduce the cost of meeting the Grid Decarbonization objective by 47% (a $632 billion undiscounted cost reduction) and by 27% including electrification (a $810 billion undiscounted cost reduction).
    c. Because GHPs reduce the cost of power on the grid, as well as the marginal system cost of electricity, which, combined with reduced fuel consumption, reduces consumer energy payments, GHPs are valuable for potentially achieving economic and environmental justice in underserved communities. Because less grid infrastructure investment is required with the large-scale deployment of GHPs, they could reduce the cost of power for *all* grid consumers—even those who do not have the technology installed.

[1] The modeling considered deployment across 68% of total building floor space in the contiguous US, which includes deployment to 43% of commercial and 78% of residential building floor space.
[2] In the Decarbonization and EFS scenarios, electric-power sector emissions are still avoided but are attributable to CO_2 policy drivers as opposed to the deployment of GHPs.

2. Consumer payments for heating fuels are reduced, resulting in a savings of $19 billion per year by 2050.[3]

3. CO_2 emissions are reduced cumulatively by 7,351 million metric tons (MMT) from 2022 to 2050 compared with the Base scenario, where 3,033 MMT reduction comes from the electric sector, and 4,318 MMT comes from the building sector (a 26% reduction in building sector emissions).

4. By the year 2050, 593 TWh/year[4] less generation is required in the Grid Decarbonization scenario, and 937 TWh/year less generation is required in the EFS scenario. These results represent reductions in overall generation requirements of 11% and 13%, respectively.

5. Even though building heating is electrified with GHP deployment—increasing winter electricity use for homes and businesses that otherwise are heated with fossil fuels—the increase is more than offset by the electricity savings from the high-efficiency performance of GHPs for summer cooling and reduced thermal loads owing to weatherization in single-family homes, resulting in substantial net reductions in grid generation, capacity, and transmission (see Figure ES-1).

6. The mass GHP deployment reduces transmission expansion requirements by 33% under the Grid Decarbonization scenario and by 38% under the EFS scenario. This amount equates to roughly 24,500 mi of transmission that can be avoided under the Grid Decarbonization scenario and nearly twice as much (43,500 mi) under the EFS scenario, which is enough to cross the average contiguous US coast-to-coast distance 9 and 16 times, respectively.[5]

7. Although outside the scope of the analysis described herein, key findings could lead to significant workforce and human health effects. The widespread GHP deployment modeled in this analysis would likely incentivize local job creation in the drilling and HVAC sectors across the US. The large emissions (e.g., CO_2, SO_x, and NO_x) reductions attributable to avoided on-site fuel combustion will similarly produce substantial local health benefits that would be realized across the country. Future work is planned to further quantify the magnitude of these benefits.

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[3] This category covers all fuels purchased for use in building heating but does not include reductions in consumer payments for heating from electric resistance heaters (e.g., baseboard heaters). The fuel cost savings are calculated as all avoided on-site fuel combustion (natural gas, propane, and fuel oil) and using the forecasted price of natural gas of $3.26/MMBtu, conservatively ignoring higher costs for propane and fuel oil for heating. For comparison, the average trading price of natural gas for the last 5 years (including the disruptions caused by the COVID-19 pandemic and the war in Ukraine) has been over $3.50/MMBtu (NYMEX natural gas data 06/14/18 to 06/14/23).

[4] For comparison, 580 TWh/year is equivalent to the output of 66 1,000-MW nuclear power plants running 24/7, 365 days a year. The EFS scenario generation reduction is equivalent to 106 1,000-MW nuclear power plants running 24/7, 365 days a year.

[5] Transmission distances were determined based on a 36.7 TW·mi and 65.3 TW·mi reduction under the Grid Decarbonization and EFS scenarios, respectively, assuming a representative 1,500-MW line capacity and an average distance from the west to the east coast of 2,800 mi for the contiguous United States.

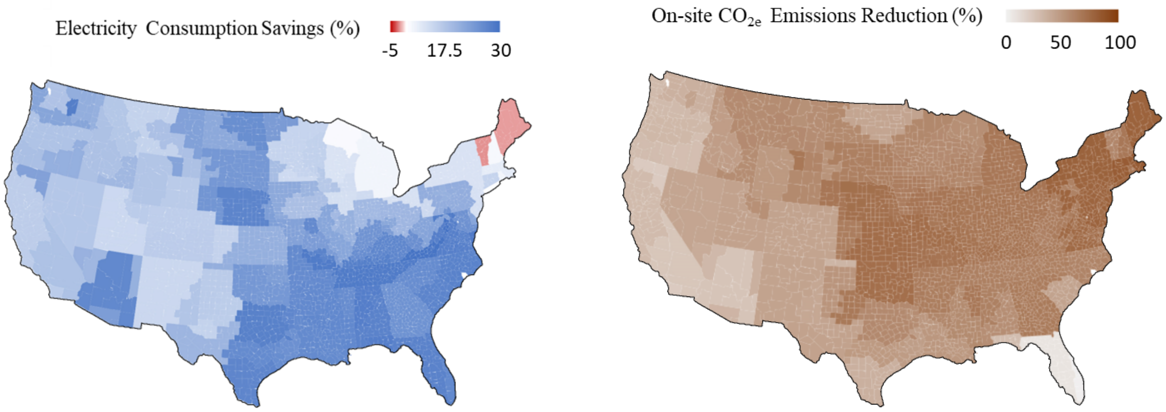

Figure ES-1. Geospatial representation of the percentage changes in (left) building annual electricity consumption and (right) carbon emissions (from on-site combustion in buildings) resulting from deploying GHPs into 68% of existing and new residential and commercial buildings in the United States, coupled with weatherization in single-family homes.

Background

Geothermal heat pumps (GHPs; also called ground source heat pumps) transfer heat to and from the ground by circulating water (or antifreeze solution in regions with cold climates) through underground piping. GHPs are well-understood to be beneficial for lowering building energy costs because of their high efficiency and ability to supply heat without fuel purchases. As a result, GHPs have zero on-site emissions. However, few studies have investigated the impacts on the electric grid of the large-scale deployment of GHPs.

This first-of-its-kind study simulates the energy use impacts of deploying GHPs into 68% of existing and new building floor space in the United States (78% of residential floor space and 43% of commercial floor space) in 14 climate zones[6] across the contiguous United States by 2050. Because this study is an impact analysis only, it does not examine the costs of and available land areas for installing GHPs in existing buildings or new constructions. Further analysis is needed to assess installation costs and needed land areas of the deployment scenarios presented in this study.

The results of this impact analysis demonstrate that savings in grid costs, CO_2 emissions, and building energy consumption are all significant. These results also demonstrate that when achieving mass deployment levels, GHPs coupled with weatherization in SFHs are primarily an electric grid cost-reduction tool and technology.

Modeling Scenarios

This study analyzed the impacts of mass GHP deployment on the electric grid through capacity expansion modeling and production cost modeling of the US electric power sector. The analysis includes a simplifying assumption that GHP deployments in this study were for individual buildings (not district-scale and/or networked systems). The building modeling accounted for weatherization in SFHs by reducing outdoor air ventilation to the minimum required by ASHRAE Standard 62.2 (ASHRAE 2007, 2016) and by eliminating air leakage from the ductwork of HVAC systems through air-sealing, which are commonly recommended practices in heat pump retrofits. According to previous studies, air-sealing can

[6] ANSI/ASHRAE Standard 169-2021 entitled *Climatic Data for Building Design Standards* (ASHRAE 2021) defines climate zones 1 through 8 as very hot, hot, warm, mixed, cool, cold, very cold, and subarctic/arctic, respectively, and sub climate zones A, B, and C as moist, dry, and marine, respectively, in several climate zones.

reduce heating energy consumption by 30%–50% (Chan 2013, Hassouneh et al. 2012, Jokisalo et al. 2009, Lozinsky and Touchie 2018, Pasos et al. 2020, Sawyer 2014). Deployment rates were fixed at 3.6% per year of existing and new building floor space that is considered applicable[7] for GHP in this study for 28 years until 2050. This study used four core scenarios.

- **Base scenario:** No GHP deployment occurs, energy consumption in new buildings between 2020 and 2050 is consistent with *Annual Energy Outlook 2021* projections (US Energy Information Administration 2021), and CO_2 emissions policies remain the same as existing state policies, including renewable portfolio standards, clean energy standards, and CO_2 emissions policies.

- **Base + GHP scenario:** The GHP deployment rate increases linearly from 0% in 2021 to 100% of all applicable buildings in 2050, which would amount to approximately 5 million GHP units installed per year. GHPs are included in new buildings starting in 2022, assuming the same energy savings as those for existing buildings.

- **Grid Decarbonization (or *Decarbonization*) scenario:** CO_2 emissions from the US electric power grid are reduced by 95% in 2035 and 100% in 2050 compared with 2005 emissions from the electric power sector.[8] This scenario indicates that all the power generation will use clean energy by 2050.

- **Grid Decarbonization + GHP scenario:** The impact of GHP deployment is incorporated into the Grid Decarbonization scenario using the same GHP deployment assumptions as the Base + GHP scenario. Both the grid decarbonization goal and the GHP deployment goal (i.e., deploying GHPs in all applicable new and existing buildings in the US) will be achieved in 2050.

Two additional scenarios were assessed in this study based on the EFS (Sun et al. 2020). These two scenarios use the same power system decarbonization pathways as the previous Grid Decarbonization scenarios.

- **EFS scenario:** No GHP deployment occurs, and economy-wide electrification of end uses—including partial building electrification through air source heat pumps (ASHPs), including the cold climate heat pumps, and other electrified devices for water heating and cooking—occurs, consistent with the values used in the high-electrification scenario from the EFS.[9] Weatherization in SFHs was not included in EFS.

- **EFS + GHP scenario:** An economy-wide electrification of end uses occurs, along with 100% GHP deployment in applicable existing and new buildings coupled with weatherization in SFHs.[10] Electrification of other end uses (not for heating and cooling) is consistent with the values used in the high-electrification scenario from the EFS.

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[7] It covers all buildings included in the original end-use load profile (EULP) data set published by the National Renewable Energy Laboratory (NREL; NREL 2021), except for buildings that use district heating/cooling, mobile homes, buildings without heating or cooling, and buildings that already use GHP.
[8] The electric-sector CO_2 emissions cap is based on the decarbonization scenario in the US Department of Energy's (DOE's) *Solar Futures Study* (DOE 2021) and is consistent with the goals in *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (White House 2021).
[9] In the EFS scenario, ASHPs were assumed to be used in 68% of residential buildings and 46% of commercial space in the United States. It is also assumed that residential ASHP efficiency will increase by 116% from 2015 to 2050 in the rapid technology development case.
[10] ASHPs in the EFS scenario are replaced with GHPs.

Impacts of Widespread GHP Deployment

The modeled scenarios described previously revealed major impacts resulting from the mass deployment of GHP systems (i.e., deploying GHPs into 68% of residential and commercial buildings in the United States, coupled with weatherization in SFHs) by 2050 in the contiguous United States.

1. **Net reduction in annual electricity consumption and greenhouse gas (GHG) emissions:** The greatest electricity savings occur in the southeastern United States, and the greatest in-building emissions reductions occur in the northern United States, as shown in Figure ES-1.

   The deployment of GHP systems has different impacts in different geographic areas (Figure ES-1). Large reductions in annual electricity consumption in the southern United States occur, for example, because energy-efficient GHPs replace widely used conventional air-conditioning systems, which dominate total annual energy use in the region.

   In the northern United States, GHP deployment results in dramatic reductions in on-site carbon emissions because GHPs replace existing combustion-based heating sources (gas, propane, and fuel oil), which emit substantial GHG emissions and other pollutants. In many regions, the gain in efficiency from GHPs during the summer cooling season more than offsets the increase in electrified winter heating load. Furthermore, weatherization in SFHs also reduces thermal loads for heating and cooling, especially in cold climates. In aggregate, this combined solution (GHP and weatherization in SFHs) results in full building electrification with reductions in total annual electricity use in most parts of the United States.

2. **Reduced need for annual power generation:** Mass GHP deployment could reduce the required annual electricity generation in the contiguous United States[11] by **585 TWh** for the Base scenario, **593 TWh** for the Grid Decarbonization scenario, and **937 TWh** for the EFS scenario, as shown in Figure ES-2.

   The major difference between the impacts of GHP deployment in these scenarios is related to the types of generation being reduced. In the Base + GHP scenario, generation is reduced across all technology types with both thermal generation and renewable technologies. In contrast, in the Grid Decarbonization + GHP scenario, the net reduction is primarily attributable to reductions in variable renewable energy (VRE) generation, such as wind and solar, and hydrogen combustion turbines (H_2-CTs), with small increases in output from nuclear power plants. The EFS + GHP scenario sees the same reductions in H_2-CTs with an increased magnitude of VRE reductions. The shift in onshore wind generation in the EFS + GHP scenario is related to reductions in winter electricity consumption under EFS as a result of replacing ASHPs (including cold climate heat pumps) with GHPs coupled with weatherization in SFHs. More details are provided in Section 4.2.1.1 of this report.

[11] This excludes Alaska, Hawaii, and US territories because of limited data for conducting a detailed analysis.

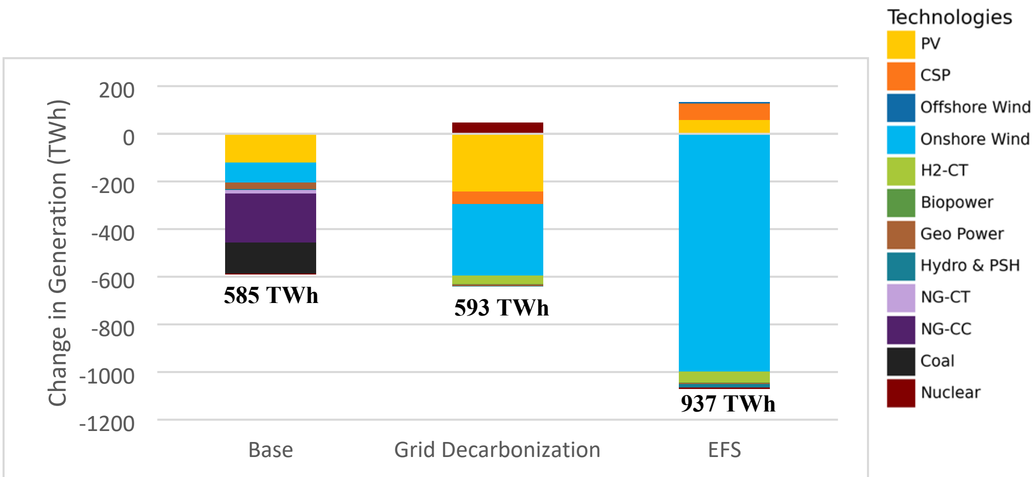

Figure ES-2. Changes in US annual electricity generation (TWh) in 2050 for Base, Grid Decarbonization, and EFS scenarios resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes. (CSP: concentrating solar power; H2-CT: hydrogen combustion turbine; NG-CC: natural gas combined cycle; NG-CT: natural gas combustion turbine; PV: solar photovoltaic; PSH: pumped storage hydropower.)

3. **Reduced need for power generation capacity and storage capacity:** Mass GHP deployment in the Grid Decarbonization scenario could double the reduction in installed generation and storage capacity achieved in the Base scenario (173 GW reduction in the Base + GHP scenario versus 345 GW reduction in the Grid Decarbonization + GHP scenario), as shown in Figure ES-3. In the EFS + GHP scenario, the installed generation and storage capacity was reduced by 410 GW.

   In the Grid Decarbonization scenario, more of the US generation mix is made up of VREs (74%–77% in the Grid Decarbonization scenario, compared with 43%–44% in the Base scenario). The Grid Decarbonization scenario also includes more battery storage than the Base scenario to improve the capacity factor of VREs. Therefore, the reduction in electricity demand resulting from GHP deployment has a greater impact on the Grid Decarbonization scenario. More details are provided in Section 4.2.1.1 of this report.

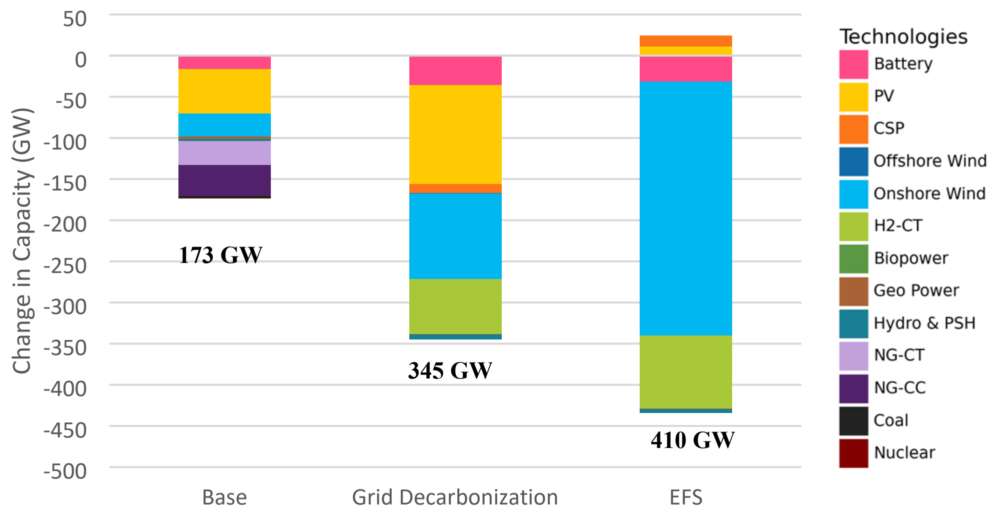

Figure ES-3. Changes in US installed power generation and storage capacity (GW) in 2050 for Base, Grid Decarbonization, and EFS scenarios resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes.

Mass GHP deployment coupled with weatherization in SFHs reduces the need for generation capacity compared with electrifying the building sector using ASHPs: Compared with electrification using ASHPs assumed in the EFS scenario, the mass GHP deployment could reduce the required electric power system capacity by 410 GW (from 3,568 GW to 3,158 GW) by 2050, as indicated in **Error! Reference source not found.**1.[12] Electrifying buildings using GHPs also reduces resource adequacy requirements compared with using ASHPs, especially in cold climate regions. More details are provided in Section 4.2.1.6 of this report.

Table ES-1. US electric power system capacity comparison in 2050

Scenario		**Total generation capacity in 2050 (GW)**	
No GHP deployment	Base	1,829	
	Grid Decarbonization	2,482	
	EFS	3,568	
			Difference
With GHP deployment	Base	1,656	173
	Grid Decarbonization	2,137	345
	EFS	3,158	410

4. **Alleviating transmission build-out requirements:** Because of the efficiency of GHPs and reduced thermal loads owing to weatherization in SFHs, less electricity generation will be needed to cool and heat buildings. Therefore, under the Base scenario, GHP deployment avoids **3.3 TW·mi**[13] transmission additions (a 17.4% reduction relative to the Base scenario without GHP), and in the Grid Decarbonization scenario, GHP deployment avoids **36.7 TW·mi** (a 33.4% reduction relative to the Grid Decarbonization scenario without GHP). Under the EFS scenario, GHP deployment avoids

[12] The total installed capacity in the EFS scenarios is much larger than in the Base and the Grid Decarbonization scenarios because of the increased demand in other sectors of the economy, including transportation and industry.
[13] Transmission deployment is measured as an increase in the capacity (terawatts) of modeled transmission lines multiplied by the length (miles) of the lines. The terawatt-mile is a common unit of measurement for transmission expansion in capacity expansion models.

65.3 TW·mi (a 37.6% reduction relative to the EFS scenario without GHP). **Assuming transmission lines have 1,500 MW capacity, a 65.3 TW·mi reduction is equivalent to 43,500 mi of transmission lines that do not need to be built—enough to cross the average contiguous US coast-to-coast distance 16 times.**

The larger reductions in the Grid Decarbonization and EFS scenarios are due to the longer transmission additions required to connect VRE resources to load centers and an increased need to flexibly move power generated with VREs over long distances. The total capital cost savings in present value in the long-distance transmission system resulting from the mass GHP deployment is $2.7 billion in the Base scenario, $29.9 billion in the Grid Decarbonization scenario, and $39.5 billion in the EFS scenario (dollar amounts in present value using a 5% discount rate). Recently, it has been more challenging to permit and construct new transmission systems; avoiding new transmission build-out through GHP deployment may have benefits beyond cost by reducing the uncertainty and delays of getting new transmission constructed to serve the needs of a decarbonized grid. More details are provided in Section 4.2.1.2 of this report.

5. **Reduced summer and winter resource adequacy requirement:**[14] Another advantage of mass GHP deployment is its impact on *capacity that can contribute toward resource adequacy*—reliable generation that is deployed in the summer and winter when demand peaks. In the Base scenario, mass deployment of GHPs means that the grid no longer needs 102 GW (summer) and 95 GW (winter) of capacity that can contribute toward resource adequacy, mostly from power plants using fossil fuels. In the Grid Decarbonization scenario, 103 GW (summer) and 101 GW (winter) of capacity that can contribute toward resource adequacy would no longer be needed. In the EFS scenario, the substitution of ASHPs with GHPs reduces the resource adequacy requirement by 127 GW in summer and 185 GW in winter.

   In the Base + GHP scenario, natural gas combustion turbines (NG-CTs) and natural gas combined cycle (NG-CC) plants are largely reduced, with the next-largest reduction being in battery storage. In the Grid Decarbonization + GHP scenario, all CO_2-emitting power plants were modeled to be retired by 2050, so the largest source of the summer capacity that can contribute toward resource adequacy reduction would come from hydrogen combustion turbines (H_2-CTs). More details are provided in Section 4.2.1.3 of this report.

[14] Capacity that can contribute toward resource adequacy differs from the installed capacity discussed previously in that it represents the portion of a generator or storage capacity that can be reliably counted on during a period of need.

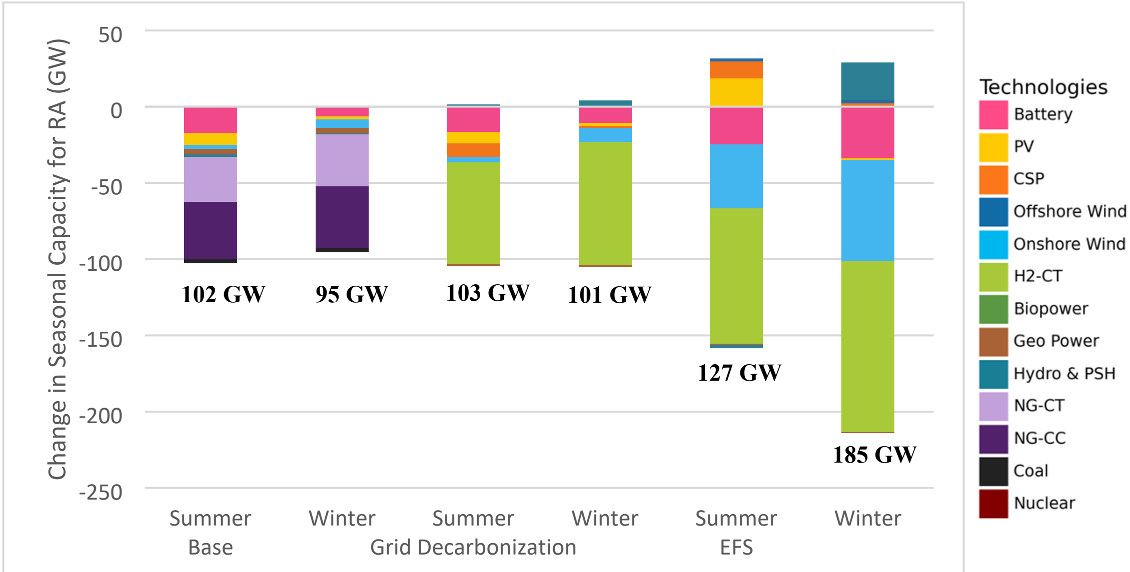

Figure ES-4. Changes in summer and winter capacity contributing to resource adequacy in 2050 for Base, Grid Decarbonization, and EFS scenarios resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes. (CSP: concentrating solar power; H2-CT: hydrogen combustion turbine; NG-CC: natural gas combined cycle; NG-CT: natural gas combustion turbine; PV: photovoltaic; PSH: pumped storage hydropower.)

6. **Reduced CO_2 emissions in the electric power system and building sector:** Compared with the Base scenario, GHP deployment will eliminate 217 MMT of CO_2 emissions each year from the US electric power system by 2050 because of the reduced total electric demand and peak load. However, in the Grid Decarbonization scenario, GHP deployment does not affect carbon emissions from the electric power system. This lack of effect is because, in the Grid Decarbonization scenario, carbon emissions reductions are built into the scenario, with the rapid 95% power system decarbonization target in 2035 and complete decarbonization in 2050. Therefore, GHP deployment rates modeled in this study do not alter the emissions from the electric power system. However, if the emissions that are avoided from the building sector through the avoided on-site fuel combustion are applied as a decarbonization credit to the grid, the net effect of GHP deployment is to achieve the emissions reduction goal of decarbonizing the grid by the year 2035. This observation is explored in greater detail in Section 4.2.1.4 of this report.

   GHP deployment could also avoid CO_2 combustion emissions related to end-use heating in the building sector. The emissions reductions in the electric power system and the building sector are counted toward the economy-wide impacts. As shown in Figure ES-5, the deployment of GHPs leads to a 7,351 MMT cumulative emissions reduction from 2022 to 2050 compared with the Base scenario, where the 3,033 MMT reduction comes from the electric sector, and 4,318 MMT comes from the building sector (a 26% reduction in building sector emissions). Compared with the EFS scenario, the mass deployment of GHPs reduces 2,178 MMT cumulative emissions from 2022 to 2050, which is from the building sector (a 16% reduction in building sector emissions).[15] More details are provided in Section 4.2.1.4 of this report.

[15] The EFS scenario had a higher share of commercial building electrification using ASHPs than the GHP retrofit scenario, contributing to the small increase in commercial building emissions.

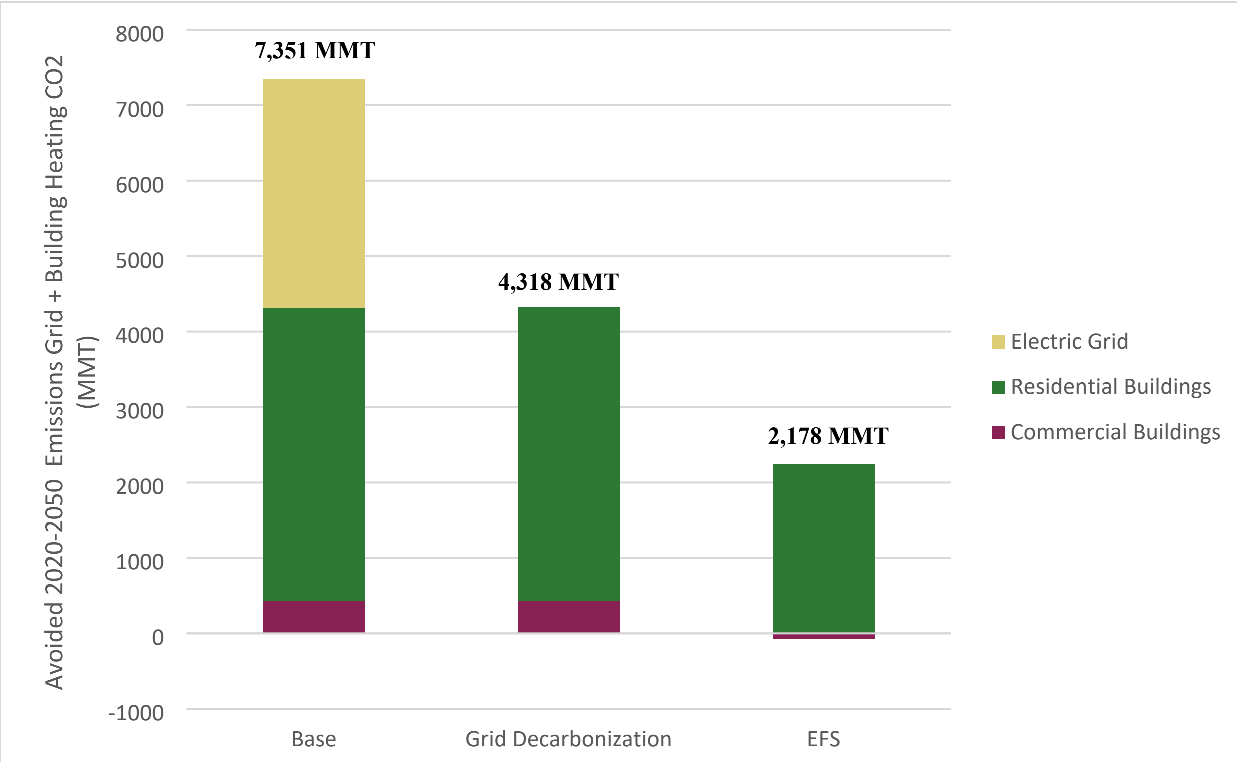

Figure ES-5. Cumulative economy-wide emissions reductions from 2022 to 2050 resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Base, Grid Decarbonization, and EFS scenarios.

7. **Reduced marginal system cost of electricity for consumers:** The marginal system cost is the wholesale cost for electricity that wholesale buyers pay to generators and grid operators. The marginal system cost ultimately affects what consumers pay to electricity providers.[16] GHP deployment reduces peak energy demand and flattens annual energy use, which lowers the marginal system cost to wholesale buyers in the Base, Grid Decarbonization, and EFS scenarios.

   As shown in Figure ES-6, the reduction in marginal system costs in the Base + GHP scenario is relatively small (6% in 2050) because many of the currently operating natural gas and coal plants have already recovered their initial investment costs. However, with GHP deployment, the increase in marginal system cost resulting from transitioning the existing grid (Base) to a decarbonized grid can be cut by nearly a third.

   GHP deployment in the Grid Decarbonization scenario reduces the new investment required to meet capacity and generation needs, yielding greater savings (a 12% reduction in 2050) in the marginal system cost than in the Base scenario. From 2022 to 2050, the reduced marginal system cost decreases wholesale electricity payments from consumers by $316 billion in the Base scenario, $557 billion in the Grid Decarbonization scenario, and $606 billion in the EFS scenario (all present values considering a 5% discount rate). More details are provided in Section 4.2.1.5 of this report.

[16] The marginal system cost comprises the locational marginal price of electricity, the marginal price of capacity for resource adequacy for the planning reserves, the marginal price of operating reserves, and the marginal credit price of renewable portfolio standards.

	Scenario	Marginal system cost in 2050 ($/MWh)		Annual payments in 2050 ($B)		Present value of cumulative electricity payments from 2022 to 2050 ($B)	
No GHP deployment	Base	49		257		3,163	
	Grid Decarbonization	83		436		4,361	
	EFS	90		636		5,460	
			Savings ($Mwh)		Savings ($B)		Savings ($B)
With GHP deployment	Base	46	3	217	39	2,848	316
	Grid Decarbonization	73	10	341	95	3,805	557
	EFS	83	7	504	132	4,854	606

Figure ES-6. Marginal system costs and payments of electricity in various scenarios.

8. **Reduced cumulative system cost of electricity:** The cumulative system cost captures the capital costs of generators and transmission systems, as well as the costs for operating the generators and the grid. As shown in Figure ES-7, GHP deployment could reduce the cumulative system cost by $147 billion (a 5.0% reduction) in the Base scenario, $246 billion (a 7.1% reduction) in the Grid Decarbonization scenario, and $306 billion (a 7.4% reduction) in the EFS scenario. The greater cost reduction in the Grid Decarbonization and EFS scenarios is mostly due to greater savings in capital costs and transmission investments compared with the changes seen in the Base scenario. More details are provided in Section 4.2.1.6 of this report.

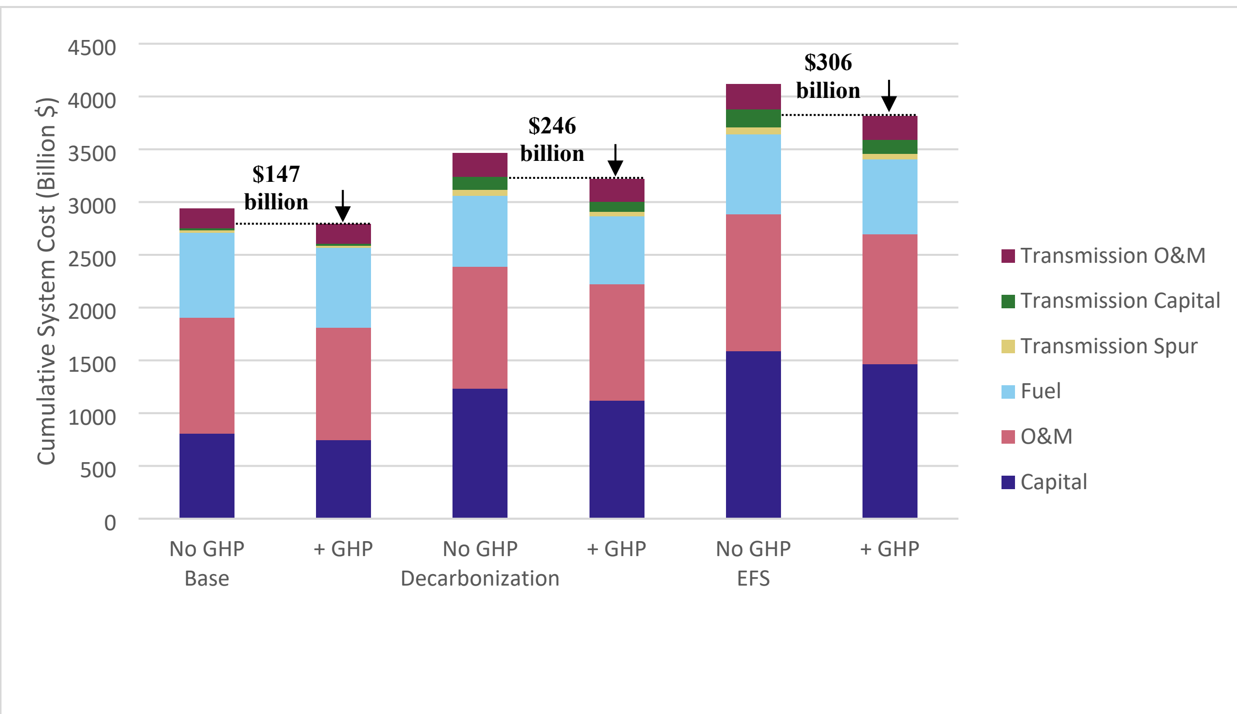

Figure ES-7. Cumulative discounted electric power system cost (present values considering a 5% discount rate) from 2022 through 2050 in various scenarios.

9. **Reduced regional peak load of electricity:** As shown in Figure ES-8, the mass GHP deployment can reduce the peak load in the summer in all reliability assessment zones (RAZs)[17] by 3%–28%. This reduction is because GHPs have a higher cooling efficiency than conventional HVAC systems. This reduction also contributes to the annual electricity consumption savings observable in Figure ES-1. The South and Southeast have higher peak load reductions than other areas because of higher cooling demand in the summer. In the winter, GHPs can also reduce the peak load for most areas; in the Southeast, where electric heating (e.g., ASHPs and electric resistance heaters) is widely used, the peak load reduction ratio can be up to 28%. Notably, the peak load is less reduced in areas where fossil fuel–based heating is used. More details are provided in Section 4.2.2.3 of this report.

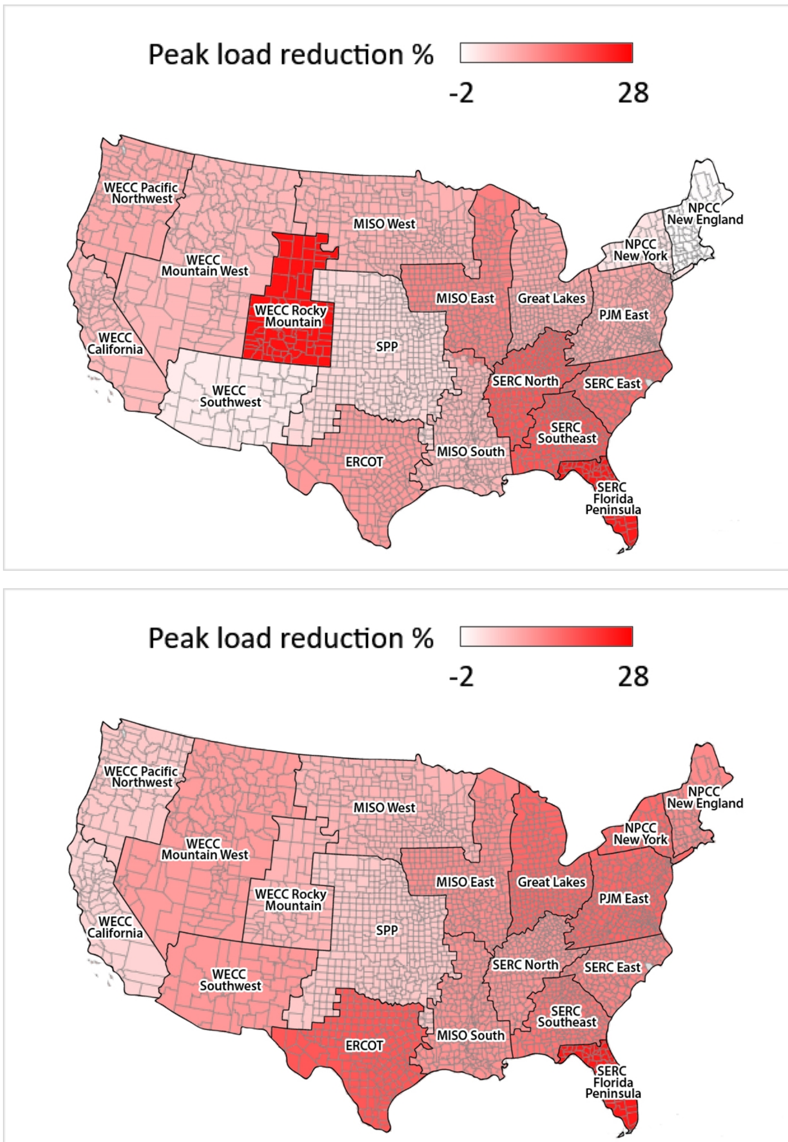

Figure ES-8. Peak load reduction ratio of the Base scenario in (top) winter and (bottom) summer resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes.

[17] The RAZs are used by the modeling program to determine regional factors beyond serving the required electric loads, such as reliability.

10. **Improved reliability of regional electric power supply:** A preliminary analysis reveals that GHP deployment can improve the operational reliability of power grids in extreme weather events. As an example, during the 2021 winter storm in Texas, approximately 28 GW (38%) of the anticipated electricity demand was left unmet during the most severe outage periods. However, if all the applicable buildings in Texas had been retrofitted with GHPs, the unserved electricity demand ratio would have been reduced to approximately 18% (10 GW). GHP deployment could thus reduce rolling blackouts, which affected many consumers and resulted in high economic losses. More details are provided in Section 5 of this report.

Study Implications

As demonstrated through this study, **the mass deployment of GHPs can electrify the building sector without overburdening the US electric power system**. In all GHP deployment scenarios considered, significant reductions are realized in the needed power generation and capacity, energy storage capacity, transmission buildouts, a seasonal capacity that can contribute toward resource adequacy, CO_2 emissions, and marginal and cumulative system costs of electricity across the United States. Although this study was for the contiguous United States only, the findings are applicable to all 50 states and US territories.

Impacts on annual electricity consumption varied geographically, with greater reductions in the southern part of the country. Meanwhile, in the northern United States, carbon emissions related to on-site heating were reduced. GHP deployment can reduce the peak load of electricity in all RAZs in the summer by 3%–28%. A similar reduction can be achieved in winter in all RAZs except in the Northeast because GHPs displace natural gas heating rather than electrified heating (e.g., ASHPs) in this region. The reduced need for electricity generation results in significant reductions in CO_2 and other emissions. This study also found that using GHPs to electrify space heating in buildings requires less electricity generation capacity than using ASHPs.

In all analyzed scenarios, deploying GHPs significantly reduces the national peak electricity demand in 2050. With the mass deployment of GHPs, less new generation capacity will be needed to meet the electricity needs of the country, reducing the required investment to expand the grid, including generators and transmission lines. Mass GHP deployment can be a key strategy to achieve decarbonization—not just for homes and communities, but for the entire grid and the broader US economy.

Moreover, the beneficial impacts of GHP deployment presented in this study may be conservative. For example, the analysis used only existing GHP technology; it did not consider GHP technology improvements over the study period. However, mass deployment of GHPs would be expected to spur in technology improvements (e.g., higher efficiency and lower cost). Because this was an impact analysis only, there is a simplifying assumption that all the GHP systems are for individual buildings. The study did not analyze the district geothermal energy networks, which have the potential for large capital expenditure reductions and improved performance. Water heating was not considered as part of this analysis but is a need that could be addressed by GHPs. The study also did not attempt to estimate domestic job creation resulting from GHP mass deployment, which is expected to be significant.

To deploy GHPs into 68% of residential and commercial buildings in the United States between 2022 and 2050, it is estimated that 5 million GHP units need to be installed each year. However, currently, only about 70,000 GHP units are installed in the US each year (Malhotra et al. 2023). This significant gap for GHP deployment needs to be addressed through technology development, supporting policies, innovative business models, and substantial investments from both the building and electric sectors.

1. INTRODUCTION

The Biden-Harris administration has set aggressive goals to reduce economy-wide emissions and achieve a 100% carbon pollution–free electric power sector by 2035 (i.e., supply-side decarbonization targets) and a net-zero emissions economy by 2050 (i.e., demand-side decarbonization targets). According to the *Annual Energy Outlook 2022* published by the US Energy Information Agency (Nalley and LaRose 2022), building heating and cooling currently represent 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 United States. Technologies to increase building energy use efficiency and reduce emissions are critical to meeting decarbonization goals.

Electrifying space heating and water heating in buildings using electric heat pumps is a method to reduce carbon emissions. Air source heat pumps (ASHPs) are the most common type of electric heat pumps in the marketplace. ASHPs extract heat from the ambient air to warm buildings or move heat to the ambient to cool buildings. The heating and cooling capacity and efficiency of ASHPs thus depend on and are limited by the ambient air conditions. The heating capacity and efficiency of ASHPs typically drop when the ambient temperature is low, and the heating demand is high. Therefore, ASHPs are usually equipped with electric resistance heaters to provide supplemental heating, which could result in high power draws when they are turned on. Mai et al. (2018), Tarroja et al. (2018), and White and Rhodes (2019) indicated that replacing gas-fired furnaces with ASHPs in the residential sector would result in higher annual electricity consumption and a shift in electric peak demand from summer to winter in regions with cold climate. Such a change could substantially affect how the power grid operates and would require substantial new investments in the electric power infrastructure.

Geothermal heat pumps (GHPs, i.e., ground source heat pumps) are another type of electric heat pump. GHPs use the ground (or sometimes water bodies such as lakes) as their heat sink/source instead of the ambient air, and they use water or a mixture of water and antifreeze as the heat transfer medium, which can transfer heat much more effectively than the air. Because of the relatively stable temperature of the ground, GHPs are more energy-efficient than ASHPs in providing heating and cooling to buildings. GHPs have been used in residential and commercial buildings in all 50 US states (Liu et al. 2019). Previous studies (e.g., Bayer et al. 2012, Liu et al. 2017, Yuan et al. 2012, You et al. 2021) reported that GHPs are typically 20%–50% more energy-efficient than conventional heating and cooling systems. Furthermore, GHPs offer a promising path to reduce economy-wide CO_2 emissions by reducing the power needed for providing space cooling and electrifying space heating, which is currently provided in many buildings by furnaces/boilers consuming natural gas, heating oil, propane, or other fossil fuels. Lim et al. (2016) reported that retrofitting residential buildings in the United States with GHPs could lead to maximum annual savings of 1.3 EJ (1.3 quad Btu) in energy, $7.1 billion in energy costs, and 64.8 million metric tons (MMT) in CO_2 emissions. Liu et al. (2019) reported that if all the existing HVAC systems in the residential and commercial sectors were retrofitted with GHPs, annual primary energy consumption could be reduced by 5.9 EJ (5.7 quad Btu), annual CO_2 emissions could be reduced by 356.3 MMT, and annual energy costs could be reduced by $49.8 billion. The 5.7 quad Btu of primary energy savings from GHP retrofits could reduce the US primary energy consumption for heating and cooling by 46%. However, these studies only assessed the impacts of GHP retrofitting on buildings. The effects of large-scale GHP deployment on the electric power sector have not been examined in previous studies.

The electric power sector represents a substantial portion of the US energy system. In 2021, the electric power sector used 38.2 EJ (36.9 quad Btu), or 38%, of the total primary energy consumption and resulted in 1,559 MMT, or 32%, of CO_2 emissions in the United States. Depending on the efficiency of the electrified heating and cooling technology deployed, implications for grid decarbonization and costs could vary significantly. Therefore, when considering the effects of heating electrification via electric heat pumps, the system-level coupling of the electric power sector with the building sector must be evaluated.

Liu et al. (2015) reported that by 2012, the cumulative capacity of GHPs installed in the United States reached 3.9 million refrigeration tons (approximately equivalent to serving 1.4 million households). Approximately 1% of the 126 million existing buildings in the United States currently use GHP systems. Major barriers that prevent the adoption of GHPs are high initial costs and spatial requirements for installing ground heat exchangers (GHEs). The US Department of Energy's (DOE's) *GeoVision* analysis (2019) predicted that the "equivalent of more than 28 million households [would be] using geothermal heat pumps by 2050." These numbers were based on market potential (i.e., only including GHP systems with a simple payback of less than 10 years), whereas economic potential (i.e., including GHP systems with a life cycle cost savings over 20 years) was far higher and would equate to 60 million households.

GHP applications have no resource limitations. The thermal storage capacity of the Earth is essentially inexhaustible from the standpoint of using GHPs in every building in the United States. Therefore, the main limiting factor is the economics. Economics is only limiting when considered at the building level instead of the system level, which accounts for both the building sector and the electric power sector. Considering the potential impacts of GHPs on the electric power sector, the economic potential at the system level could be greater than that projected in the *GeoVision* analysis (2019).

A recent report from the American Council for an Energy-Efficient Economy indicated that energy efficiency measures that reduce building thermal loads for heating and cooling, including building envelope improvements and HVAC system upgrades, are likely to contribute the most to energy savings and avoided electricity system costs. These energy efficiency improvements can also help mitigate many of the challenges associated with high levels of renewable energy deployment, including critical materials mining, land acquisition, transmission siting, and long renewable energy interconnection queues. Therefore, an aggregated set of energy efficiency measures should be part of any deep decarbonization or high renewable energy pathway study (Specian and Bell-Pasht 2023).

In this study, the effects of heating and cooling electrification via GHP deployment across the contiguous US,[1] which includes weatherization in single-family homes, are comprehensively analyzed for the first time. Specifically, this study investigates the national-scale benefits that GHP deployment could provide for, including

- reducing energy consumption and the associated carbon emissions,
- shedding peak electricity demand,
- lowering grid infrastructure costs, and
- improving grid operational reliability.

To facilitate the modeling and analytical work, a workflow was developed and used to effectively manage substantial project scales and underlying complexities. In this workflow, commercial and residential building GHP retrofits were first modeled individually and then aggregated to quantify the associated impacts on each balancing area (BA) of the electric energy system. Then, these building-related impacts were considered via grid modeling to evaluate the effects of GHP retrofits on the electric power sector.

The remainder of this report is organized as follows. Section 2 introduces the methodology and data sources used to evaluate the impacts on energy consumption and carbon emissions that would result from

[1] This excludes Alaska, Hawaii, and US territories because of limited data for conducting a detailed analysis. Although this study was for the conterminous United States only, the findings are generally applicable to all 50 states and U.S. territories.

a mass deployment of GHPs in the United States. Section 3 presents the building sector analysis results, and Section 4 describes the electric power sector analysis results. Section 5 presents a preliminary regional grid reliability analysis. Finally, Section 6 provides conclusions and a discussion on future work.

2. ANALYSIS METHODOLOGY

The procedure for analyzing the effects of mass GHP deployment on the US electric grid includes two stages, as depicted in Figure 2-1. In the first stage, the impacts of GHP retrofits on the energy consumption and electricity demand of residential and commercial building stocks were quantified for each county in the United States and aggregated across the contiguous United States. In the second stage, the difference in hourly electricity use that resulted from the GHP retrofits was used as an input in the grid modeling tools to evaluate the impacts of GHP retrofits on the electric power sector.

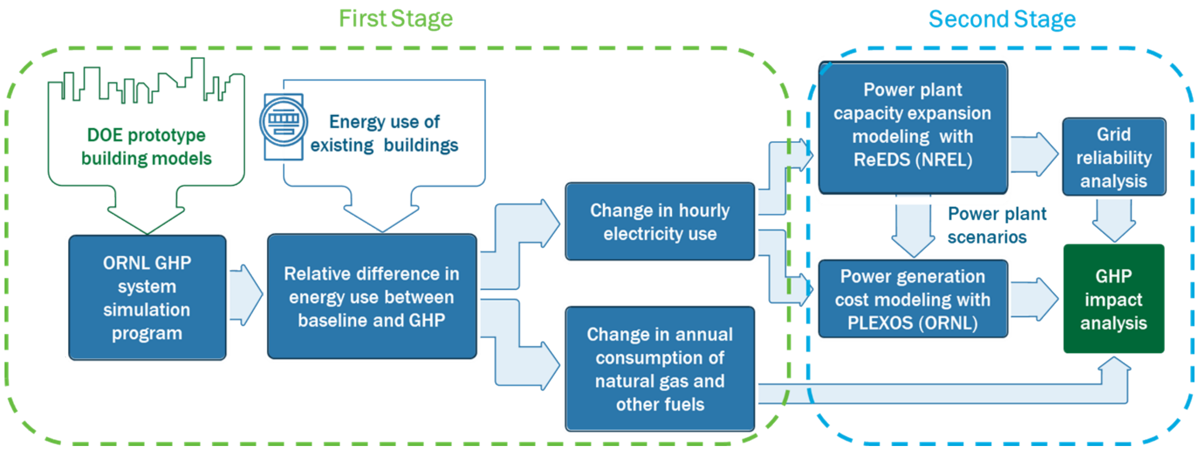

Figure 2-1. Flowchart of the combined building and grid modeling approach.

2.1 BUILDING SECTOR MODELING

2.1.1 New End-Use Load Profiles of Existing Buildings Resulting from GHP Retrofits

Existing buildings have diverse characteristics and operation schedules that must be considered when calculating their end-use load profile (EULP), which is the pattern of building energy use at each hour of the year. This study used the EULP data set published by the National Renewable Energy Laboratory (NREL; NREL 2021) for the existing US building stock in 2018[2] (does not include any new buildings after 2018) as the baseline energy use for assessing the impacts of GHP retrofits. Approximately 1 million EULPs are included in the data set, representing all major end uses (e.g., space cooling, space heating, fan, pump, lighting, equipment, water heating) in various building types and climate regions in the US commercial and residential building stocks. These EULPs are generated with sub-hourly simulations of millions of different buildings across all US counties using the ResStock and ComStock programs, which are physics-based building stock modeling tools. These models have been informed by and validated against the best-available ground-truth data (NREL 2021).

New EULPs that result from retrofitting all applicable residential and commercial buildings in the United States with new GHP systems were calculated in this study. Only HVAC-related end uses (i.e., space cooling, space heating, fan, and pump) were adjusted in the new EULPs. Air sealing (e.g.,

[2] NREL's EULP data covers 57% and 98% of the floor space of the commercial and residential buildings, respectively, that exist in 2018.

weatherstripping of windows and doors, blocking air leakage through ductwork and ceiling) was also accounted for when calculating new EULPs for single-family homes because it is a typical practice associated with GHP retrofits. Although GHPs can also contribute to water heating for part or all of the year depending on the design, using GHPs for water heating was not included in the new EULP. Figure 2-2 illustrates the following steps for calculating the new EULPs:

- Calculate energy consumption after replacing existing HVAC systems in DOE's prototype models for existing buildings (DOE 2022) with new distributed GHP systems using the GHP simulation program developed at DOE's Oak Ridge National Laboratory (ORNL) (Liu et al. 2022).

- Calculate hourly relative differences (i.e., fraction factors) in the HVAC-related site energy consumption between the existing HVAC system and the new GHP system for each prototype building in 14 US climate zones (CZs).[3]

- Identify valid candidates for GHP retrofits by using the metadata summary of the residential and commercial building stock characteristics in the original EULP data set. In this study, all buildings included in the EULP data set were considered valid for GHP retrofits except for buildings that use district heating and cooling (i.e., no energy consumption for heating and cooling at the building), mobile homes, buildings without heating or cooling, and buildings that already use GHPs.

- Apply the fraction factors to the original EULPs that are applicable candidates for GHP retrofits to determine the new EULPs that result from the GHP retrofits.

The original and new EULPs were aggregated for each BA, and the differences between the aggregated original and new EULPs were calculated to determine the changes in hourly electricity consumption and fossil fuel use in each BA. Additionally, the resulting carbon emission reductions from reduced fossil fuel consumption on the building sites in each BA were calculated using carbon emission factors of various fossil fuels (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE] 2022). The carbon emission reductions related to changes in electricity use are reported in Section 4.

[3] Based on heating and cooling degree-days, (ASHRAE 2021) defines CZs 1 through 8 as very hot, hot, warm, mixed, cool, cold, very cold, and subarctic/arctic, respectively, and sub-CZs A, B, and C as moist, dry, and marine, respectively.

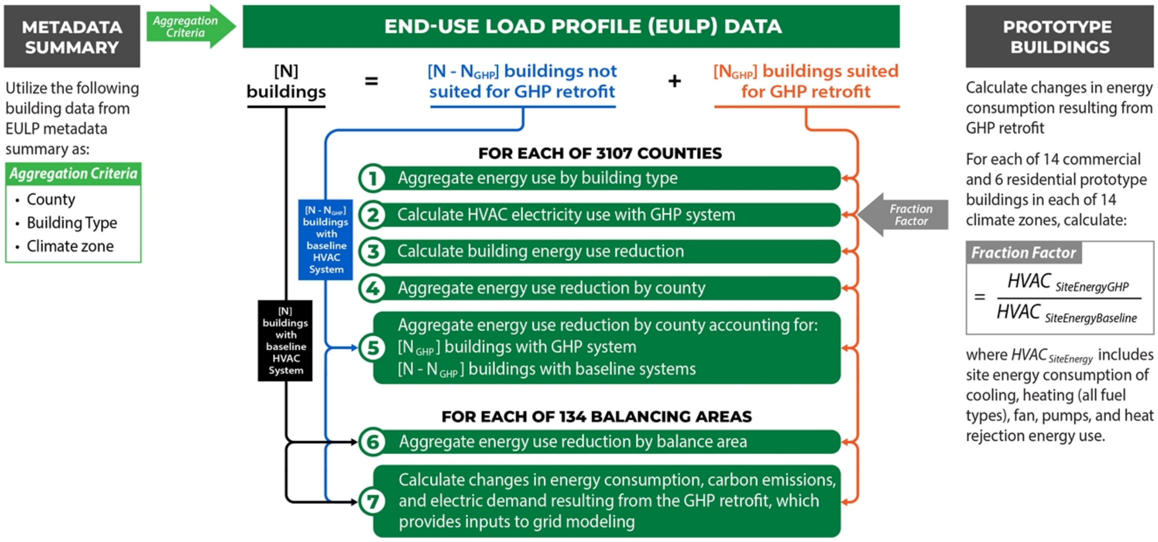

Figure 2-2. Procedures for calculating energy savings and carbon emission reductions in existing buildings resulting from GHP retrofits.

2.1.2 GHP Simulation Tool

ORNL's GHP simulation program (Liu et al. 2022) was developed to establish a fully automated process for (1) replacing an existing HVAC system submodule in a building energy simulation model with a distributed GHP system; (2) sizing each component of the GHP system, including heat pumps and vertical bore GHEs (VBGHEs); and (3) simulating the performance of the existing HVAC system and the GHP system to compare the differences. The data flow of the automated process is shown in Figure 2-3. A web interface was also developed to take user inputs and display simulation results.

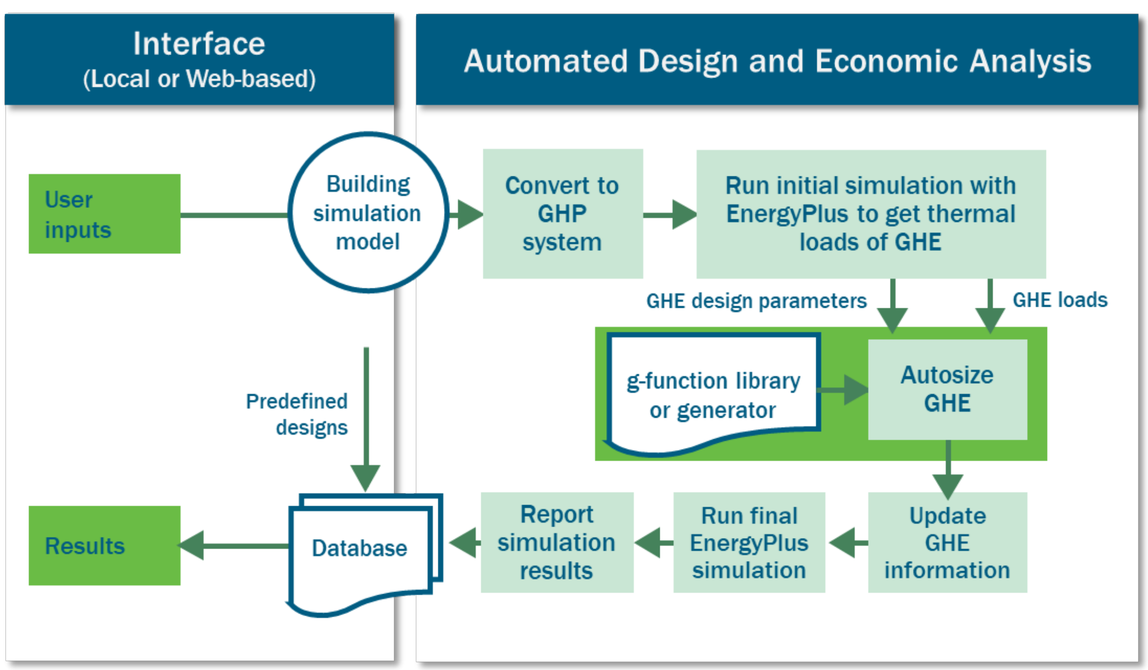

Figure 2-3. Flowchart of ORNL's GHP simulation program.

2.1.3 Prototype Building Models

DOE's prototype building models (DOE 2022) of 16 types of commercial buildings and 4 types of single-family homes (SFHs) in 14 US CZs were used in this study. Each prototype building model has a submodule for an HVAC system that is commonly used in buildings represented by the prototype model. The third edition (the latest) of typical meteorological year (TMY3) weather data (Wilcox and Marion 2008) of representative cities of these CZs were used in the energy simulation with these prototype models. To represent average existing buildings, this study used the prototype commercial building models created following the 2007 edition of ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2007) and the prototype SFH models created following the 2006 edition of the International Energy Conservation Code (IECC) (ICC 2006). Characteristics of the prototype building models used in this study and the representative cities of the 14 US CZs are listed in Appendix A.

2.2 ELECTRIC POWER SYSTEM MODELING

The electric power system in the 48 contiguous US states is divided into 134 BAs, as indicated by the boundary lines and numbered in white circles in Figure 2-4, consistent with other NREL grid modeling studies. The boundary lines generally follow the lines of real BAs but are adjusted in some instances to follow county lines instead of actual BA territory lines and to absorb small BAs into single larger regional BAs (for example, BA 10 in California encompasses several smaller BAs). Although counties are the spatial resolution of the building sector modeling, BAs are the spatial resolution at which generation, load, and transmission are balanced in the grid modeling. The map also shows the reliability assessment zones (RAZs), which are indicated with various colors on the map, to which each BA is assigned. The RAZs are used by the modeling program to determine regional factors beyond serving the required electric loads, such as reliability. The colors on the map simply indicate that each RAZ comprises multiple BAs.

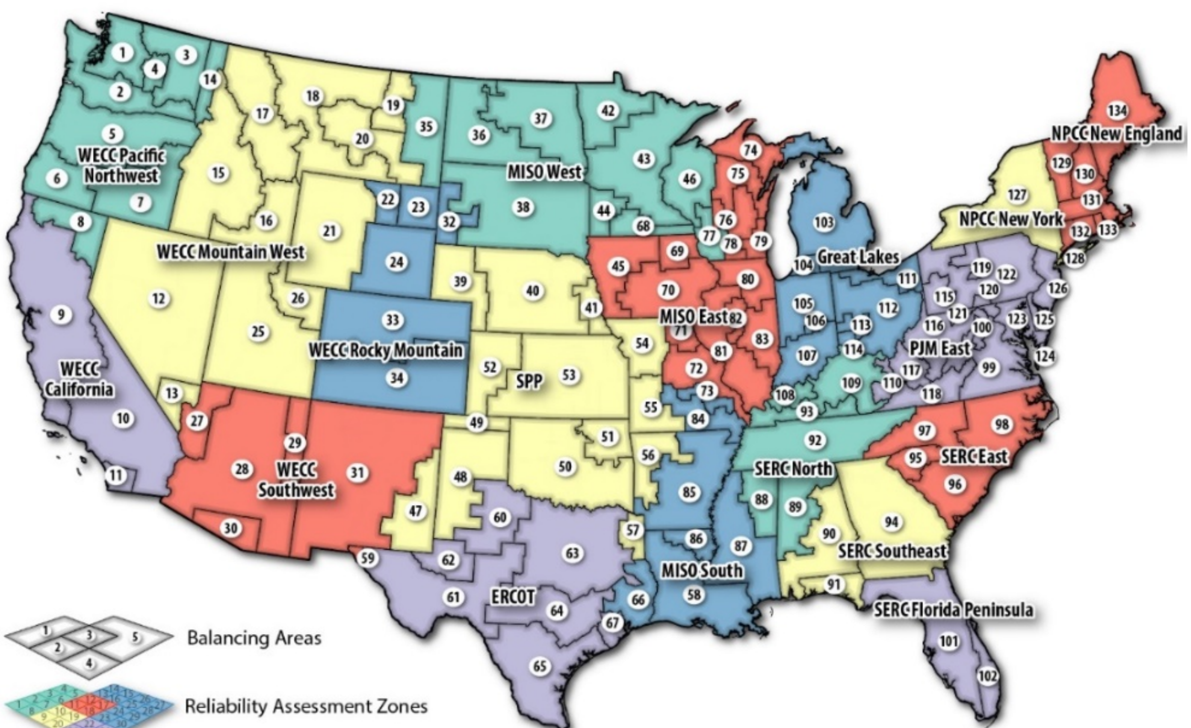

Figure 2-4. BAs of the contiguous US electric power system modeled in this study.

Two grid modeling methodologies—capacity expansion modeling (CEM) and production cost modeling (PCM)—were performed sequentially to analyze the effects of mass GHP deployment on the electric power sector. CEM is used to identify the least expensive mix of power generation in each BA over multiple decades. It takes into consideration factors such as new policies, technological advancements, changing fuel prices, and electricity demand projections. CEM is not suited to detailed, hour-by-hour simulation of power plants and grid operations. Other analyses, such as PCM, are needed alongside CEM to capture the full spectrum of the planning and operations of the electric power sector and to predict the cost and emission impacts of mass GHP deployment. PCM seeks to minimize the total cost of operating a fleet of generators to satisfy electricity demand and requirements for ancillary services. The minimization is achieved by controlling the commitment and dispatch of generators while adhering to system-level constraints on transmission capacity and generators' physical or operational limitations.

Regional Energy Deployment System Model (ReEDS), a publicly available CEM tool developed at NREL, is used to predict power system planning. It forecasts the time, location, and quantity to install new generation resources (e.g., renewable energies, fossil fuel–based units, storage systems, nuclear units) and transmission lines, accounting for the load growth and retirement of aging infrastructure in the future. The outputs of ReEDS include generation capacity, generator builds and retirements, high-level results on carbon emissions and fuel consumption, and so on.

PLEXOS, a commercial software for PCM, is used to simulate power systems' operation at hourly or finer resolution. For a given power system infrastructure, PLEXOS can optimize the operating schedule for power systems to minimize operational costs. The PLEXOS simulation outputs are in fine time resolutions, such as the online/offline status of a generator in several days, the hourly power output of a generator, and the hourly electricity prices. It can also analyze reliability indexes, such as total unserved load, power interruption, outage duration, and outage frequency.

The flowchart of the grid sector analysis is shown in Figure 2-5. The changes in hourly electricity use in the building sector of each BA resulting from the mass GHP deployment are added to the electric load profile of the BA to obtain a new BA load profile, which is used as the input of ReEDS. ReEDS simulation is performed using a representative set of time slices for multiple specific years to predict the needed generator build/retirement, generation capacity, and renewable energy penetration that are required to meet the new load profile. The time slices are composed of overnight, morning, afternoon, and evening average hours for each season, and a 17th time slice selected from the 40 top summer peaking hours is included to capture higher peak operations. A translation process is employed to translate the generation, storage, and transmission network topology results from ReEDS into inputs of PLEXOS to perform the hourly modeling of grid operations and predict hourly power generation, carbon emissions, fuel consumption, and annual peak demand of the electric power sector. Thus, PLEXOS can capture more details of electric power systems' operations and associated costs compared with the 17 time slices of operations used during ReEDS optimization.

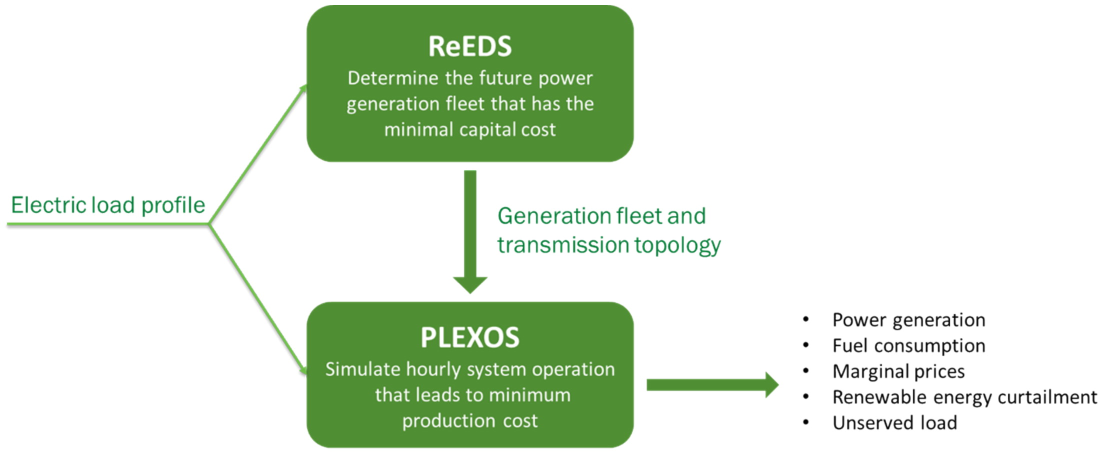

Figure 2-5. Flowchart of the electric power sector analysis.

3. BUILDING SECTOR ANALYSIS

The impacts of the mass deployment of GHP systems in commercial and residential buildings were evaluated by comparing the original EULPs of the existing building stock and the new EULPs resulting from retrofitting all buildings included in the original EULPs with GHPs, except for buildings that use district heating/cooling (i.e., no energy consumption for heating and cooling at the building), mobile homes, buildings without heating or cooling, and buildings that already use GHPs. The scenarios and assumptions used in the building modeling and the results are presented here, along with discussions of the limitations of this study.

3.1 SCENARIOS AND ASSUMPTIONS

In this study, distributed GHP systems were modeled for retrofitting existing HVAC systems in commercial and residential buildings. The distributed GHP system is typically coupled with a dedicated outdoor air system (DOAS) (Kavanaugh and Rafferty 2015), as shown in Figure 3-1. This system configuration separates outdoor air (OA) ventilation from the temperature control in each zone so that it can maintain the indoor air temperature at a user-specified set point while ensuring that only the needed OA is delivered to each zone of the building. The following assumptions were used in the simulations:

- The GHP system is sized to meet 100% heating and cooling demands in each thermal zone without using any supplemental heating or cooling.
- The heating coefficient of performance (COP) of the GHP is 4.0 and the cooling COP is 6.5 at the rating conditions specified in the ANSI/AHRI/ASHRAE/ISO Standard 13256-1 (2012). These COPs are 10%–30% higher than the minimum requirements specified by ENERGY STAR.[4] The operational efficiency of each GHP during each hour of its annual operation is modeled using the performance curves of a typical GHP, which correlate the operational heating and cooling capacity and efficiency of the GHP with the simulation-predicted supply fluid temperature of the VBGHE in response to the heating and cooling loads of the GHP.[5] The performance curves of GHPs are listed in Appendix B.

[4] https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal/key_product_criteria
[5] Some GHPs can use the condensing heat during cooling mode operation to preheat domestic hot water so that the heat rejection load to the VBGHE is reduced. However, this feature was not accounted for owing to the limitations of the simulation program used in this study.

- Each building has its own VBGHE, which comprises boreholes laid out in a square or near-square array and with uniform spacing between boreholes.[6] The design parameters of the VBGHE are listed in Table 3-1. The required number of boreholes and borehole depth of each VBGHE are autosized with ORNL's GHP simulation program (Liu et al. 2022, Spitler et al. 2022) based on the thermal loads and the VBGHE's design parameters. Each VBGHE is sized to maintain its supply fluid temperature between 1°C and 35°C year-round.[7]

- For commercial buildings, the DOAS delivers unconditioned OA to the return air of the GHP in each thermal zone. For SFHs, an energy recovery ventilator is used in the DOAS to preheat or cool the OA before it enters the building.

- Air sealing[8] is applied to SFHs as a part of GHP retrofits to reduce outdoor air ventilation to the minimum required by ASHRAE Standard 62.2 (ASHRAE 2007, 2016)[9] and to eliminate air leakage from the ductwork of the HVAC system. Air sealing can reduce the heating and cooling load, especially in cold and hot climates. Air sealing can make GHP retrofits more cost-effective because it reduces the required capacity of a GHP and the size of ground heat exchangers, which may offset the cost of air sealing and save more energy. The impact of OA infiltration and ductwork leakage on the annual heating and cooling energy consumption of SFHs at each CZ is presented in Appendix C.

- Fans used in the new GHPs are more energy-efficient than the fans used in the existing HVAC systems. Fan efficiencies and pressure rise of the existing residential HVAC system and the new GHP are listed in Appendix B.[10]

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[6] We don't have information on the available land area for installing boreholes at each applicable building. We assume that, with the development of drilling technologies, such as compact drill rigs and tilted angle drilling, as well as the wide adoption of district GHP systems, there could be solutions to drill needed boreholes.
[7] Recent work has identified that in areas with mixed building types, the use of a shared VBGHE can greatly reduce the number of vertical boreholes that must be drilled (Spitler et al. 2022).
[8] Air sealing is usually done by applying weather strips at windows and walls, spraying foams in the attic, filling the cracks in the foundation and walls, and sealing the ductwork of the HVAC system.
[9] According to ASHRAE Standard 62.2 (ASHRAE 2007, 2016), the minimum OA ventilation requirement for acceptable indoor air quality in low-rise residential buildings is 0.35 air change per hour. However, the OA ventilation rate (including mechanical ventilation and infiltration) of the prototype SFH models developed based on the 2006 edition of IECC is 0.84 air change per hour, which is typical for old existing SFHs (Yamamoto et al. 2010).
[10] Most commercial HVAC systems use central air distribution systems, which typically use large, variable-speed fans to supply air throughout the building via central ductwork. These fans are quite different from the fans of GHPs, which only circulate a small amount of air within a thermal zone.

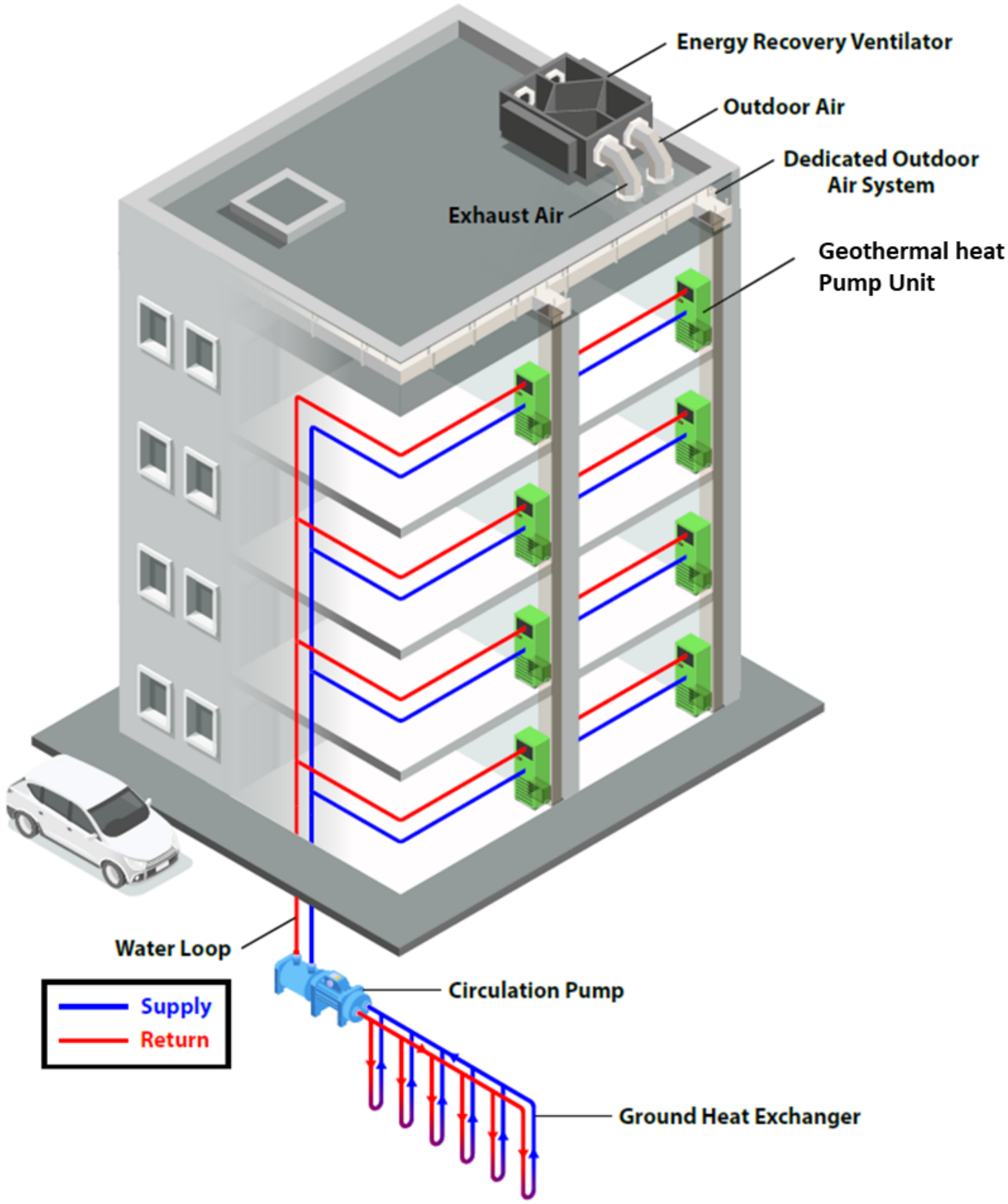


Figure 3-1. Illustration of a distributed GHP system coupled with a DOAS.

Table 3-1. Default values of VBGHE design parameters

Parameter	Default value	Parameter	Default value
Borehole radius (m)	0.0762	Grout heat capacity (kJ/[m^3·K])	3,901
U-tube pipe thickness (m)	0.002	Ground conductivity (W/[m·K])	1.29
U-tube pipe outer diameter (m)	0.027	Ground heat capacity (kJ/[m^3·K])	2,347
U-tube leg spacing (m)	0.025	Undisturbed ground temp. (°C)	Site-specific and calculated with the method by Xing et al. (2016)
Pipe conductivity (W/[m·K])	0.39	Bore spacing (m)	6.1
Pipe heat capacity (kJ/[m^3·K])	1,542	Maximum GHE supply temp. (°C)	35
Grout conductivity (W/[m·K])	1.29	Minimum GHE supply temp. (°C)	1

To represent existing commercial buildings, the DOE commercial prototype models (Pacific Northwest National Laboratory 2018) created following the 2007 edition of ANSI/ASHRAE/IES Standard 90.1 were used in this study. The 2007 edition was selected because buildings built or retrofitted around 2007 likely followed the 2007 edition of the building energy standard, and the HVAC systems in these buildings have reached their lifetime at the time of this study (2023) and need to be replaced with a new system. Similarly, the DOE residential prototype building models (Mendon et al. 2012) created following the 2006 edition of the IECC standard were used in this study to represent the existing residential buildings.[11]

3.2 HEATING ENERGY SOURCES OF EXISTING BUILDINGS

The energy sources for space heating in residential and commercial buildings were analyzed using the metadata of NREL's EULP data set. Figure 3-2 shows the percentages of total existing building floor space heated with various energy sources. This figure only shows the heating energy sources of the buildings that are considered applicable for GHP retrofits (i.e., excluding buildings with district heating and cooling, mobile homes, buildings without heating or cooling, and buildings that already use GHPs), which accounts for 78% of the total conditioned space of all existing residential buildings and 43% of the total conditioned space of all existing commercial buildings. In total, 241 billion ft^2 of floor space in the residential and commercial buildings are included in this study for GHP retrofits. As shown in Figure 3-2, although natural gas is the predominant heating energy source, a significant number of buildings are heated with electricity using electric resistance heaters or heat pumps (mostly ASHPs).

[11] Future buildings were not modeled explicitly in this study. The same energy savings percentages in the existing buildings are approximately applied to the future buildings in the grid analysis. This limitation is discussed in Section 3.4.

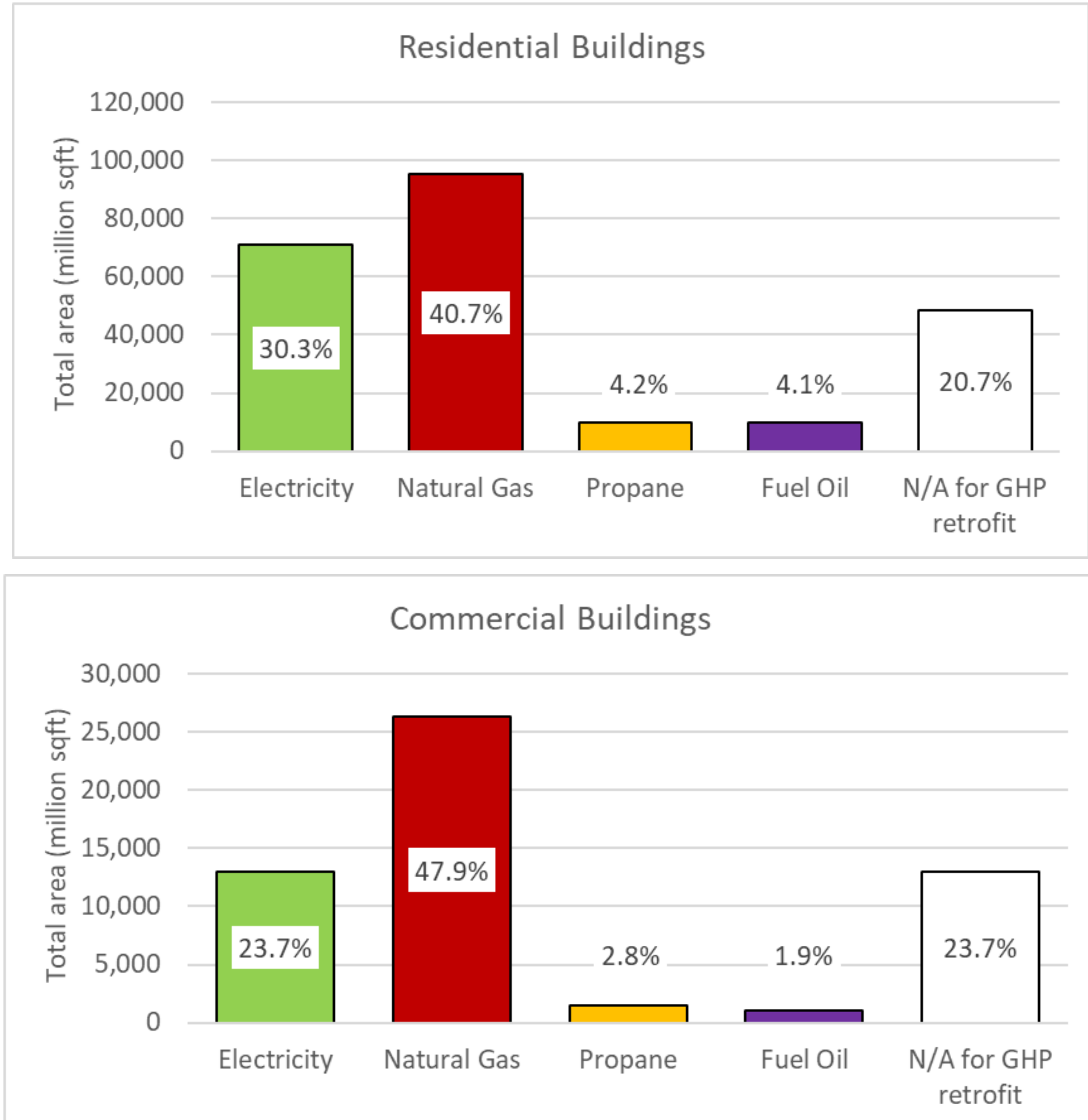


Figure 3-2. Existing residential and commercial building floor space heated by different sources. The white columns represent the amount of existing floor space that is not considered for GHP retrofits in this study.

The two stacked bar charts in Figure 3-3 show the space heating energy use in residential and commercial buildings, respectively, in each BA. Each stacked bar represents the contribution of various heating energy sources to the total space heating energy of all the buildings that are applicable for GHP retrofits in each BA. A BA map is shown in Figure 2-5. The percentages of heating energy sources vary widely across BAs. In some BAs in the Northwest region, such as BA 2 in Washington State, the share of electric heating was greater than 60%. However, the share of electric heating was less than 10% in most BAs in the Northeast region, such as BA 128 in New York state.

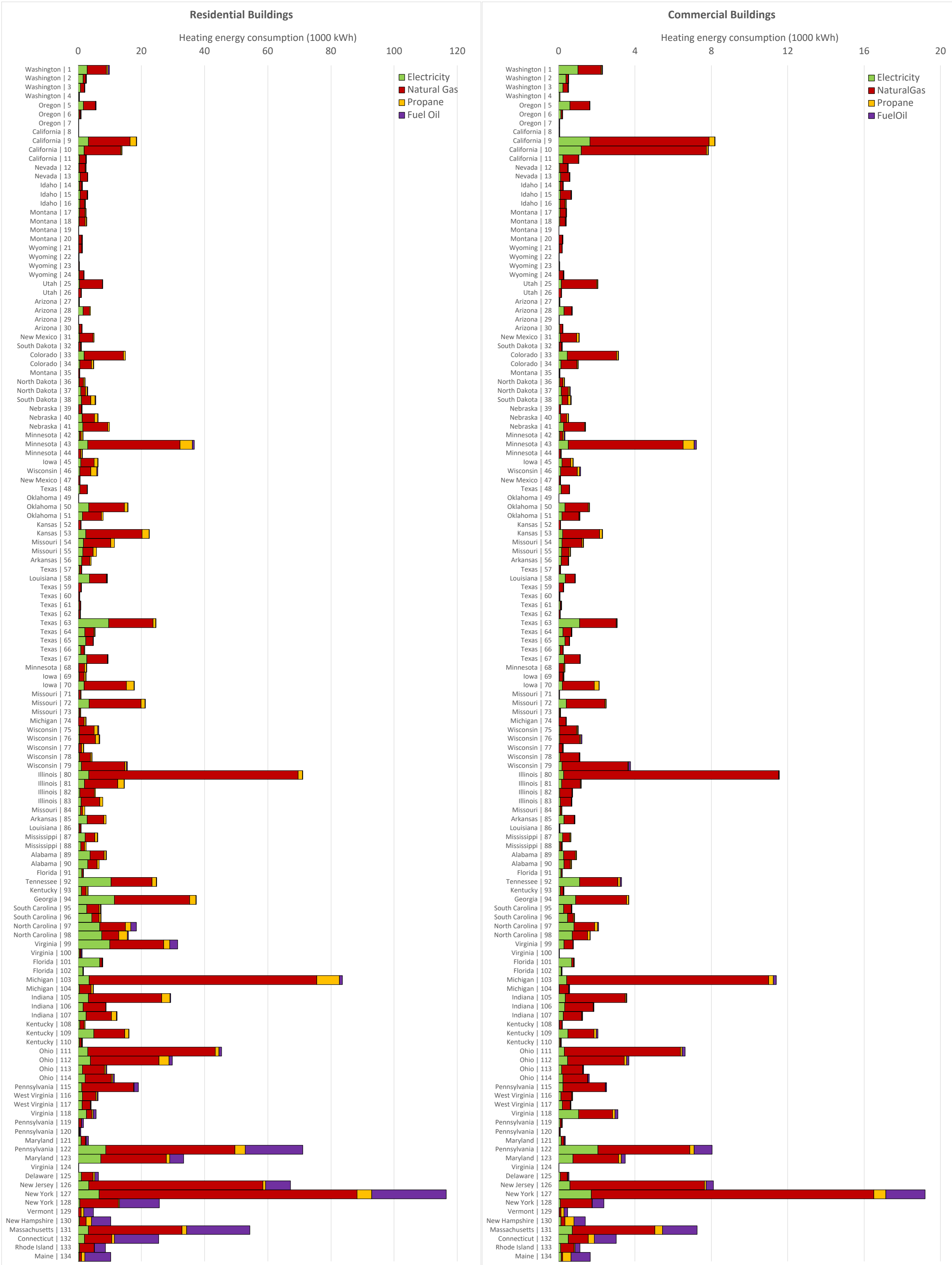


Figure 3-3. Percentages of various energy sources used for space heating in each BA for existing buildings that are applicable for GHP retrofits.

3.3 ANALYSIS RESULTS

The results of building sector analysis indicate that mass GHP retrofits (including weatherization in SFHs) have significant potential to reduce energy consumption and carbon emissions. If all applicable buildings in the contiguous United States were retrofitted with GHPs at once, electricity usage would be reduced by 401 TWh, which is an 18% reduction from the baseline EULP each year. Furthermore, 5,138 billion MJ of annual fossil fuel (e.g., natural gas, heating oil, propane) consumption (approximately 4,747 billion ft^3 of natural gas equivalent) would be eliminated. The reduced on-site fossil fuel consumption at buildings would avoid 342 MMT of equivalent carbon emissions each year. The emissions reduction resulting from the reduced electricity consumption are discussed in Section 4. The geospatial characterization of the impacts of GHP retrofits in each BA is presented here.

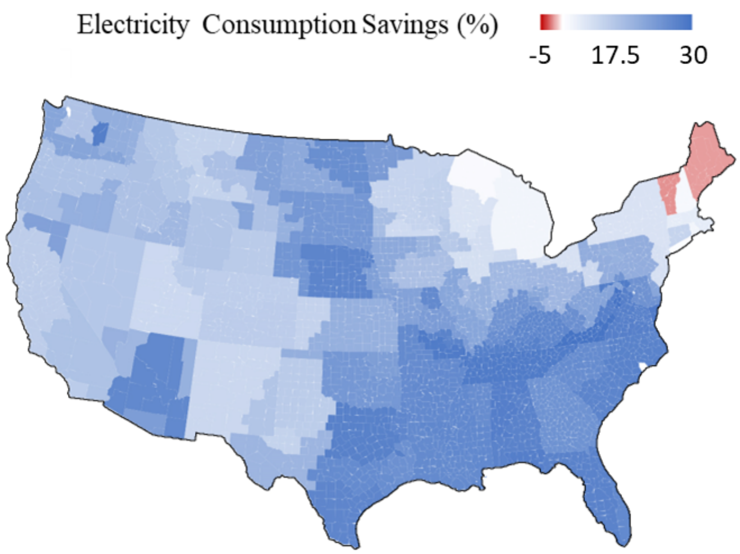
3.3.1 Geospatial Characterization of the Impacts

Because of the different heating and cooling demands in each BA and the various energy sources used for providing space heating in the existing HVAC systems, regional differences exist in the effects of GHP retrofitting. According to the US Energy Information Agency (EIA; EIA 2021), more than 99% of existing HVAC systems consume electricity to provide space cooling. GHPs reduce electricity consumption for space cooling because they are more efficient than all other commonly used 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 heater or ASHP), it will reduce electricity consumption for space heating. However, if it replaces fuel-burning heating equipment, it will eliminate fuel consumption and use electricity for space heating. Therefore, in southern BAs, where the cooling demand is high and more than 40% of space heating is provided with electricity, GHP retrofitting will result in significant savings in electricity. In contrast, because most space heating in northern BAs is provided by fossil fuels, the GHP retrofits will result in increased electricity consumption in the heating season, which will offset part of the electricity savings obtained during the cooling season; in limited examples (VT and ME), this offset may even slightly increase annual electricity consumption. Therefore, electricity savings gained from GHP retrofits in northern BAs are not as significant as in southern BAs. However, compared with the electricity consumption increase that would result from electrified heating with ASHPs, as demonstrated in this report and documented in previous analyses such as the *Rhode Island Strategic Electrification Study* (Erickson et al. 2020), GHP deployment (including weatherization in SFHs) achieves electrified heating with lower electricity consumption than the alternative, resulting in significant avoided costs and carbon emissions. Furthermore, the difference in energy efficiency between GHPs and conventional HVAC systems for cooling (e.g., a GHP with a cooling COP of 6.5 vs. a chiller with a cooling COP of 5.0) is smaller than that for heating (e.g., a GHP with a heating COP of 4.0 vs. a natural gas furnace with a burner efficiency of 0.8). Therefore, the site energy reduction would be higher in northern BAs, where buildings have greater heating demands.

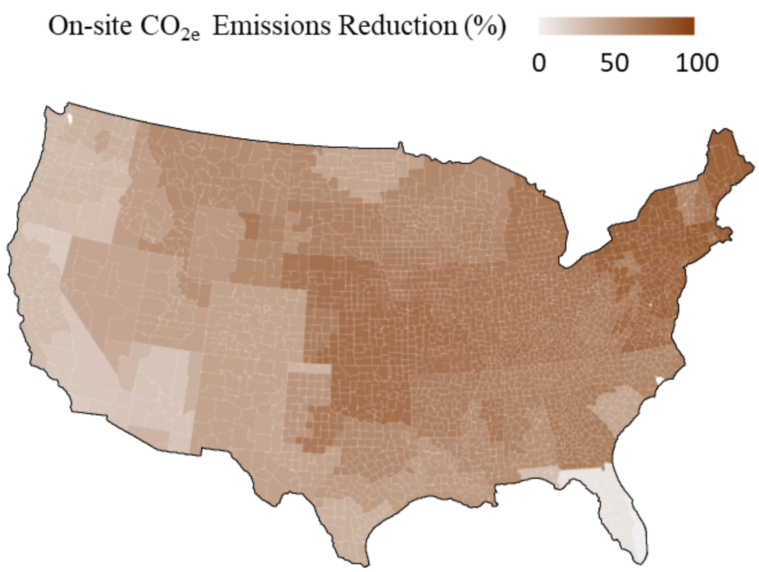
Figure 3-4 shows a geospatial representation of the percent changes in annual electricity consumption, site energy consumption, and on-site carbon emissions that result from the mass deployment of GHPs in each BA. Figure 3-4(a) shows that retrofitting the existing HVAC systems with GHPs and weatherization in SFHs will reduce electricity consumption in most parts of the United States, except in a few BAs in the Northeast. More significant reductions in annual electricity consumption will be achieved in southern BAs. On the other hand, Figure 3-4(b) shows that GHP retrofits result in higher percentages of carbon emission reductions (counted with CO_2 equivalent [CO_2e] of various emissions from combustion of fossil fuels[12]) in northern BAs (colder climates) than in southern BAs. Buildings in northern BAs have a higher burden for electrification of heat because of a higher heating load (in total energy and peak demand), so

[12] The CO_2-equivalent means the number of metric tons of CO_2 emissions with the same global warming potential as 1 metric ton of another GHG.

on average for the year, the electricity savings are not as significant and in some cases are negative. However, GHP retrofits eliminate high–CO_2 emitting, low-efficiency fossil fuel consumption for heating. Therefore, the overall site energy savings (including changes in electricity and fossil fuel consumption) on average are higher in northern BAs. Furthermore, as discussed in Section 4, to electrify all buildings' heating and cooling, the GHP retrofits investigated in this study would use less electricity compared with replacing existing HVAC systems with ASHPs.



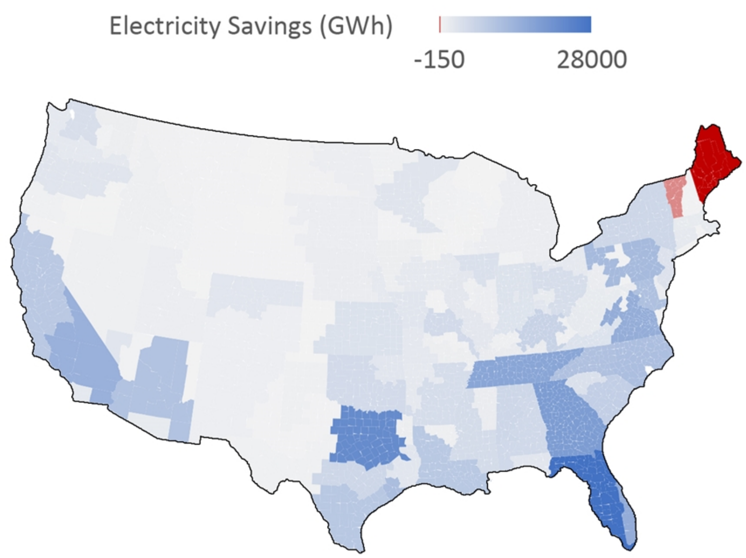
(a)



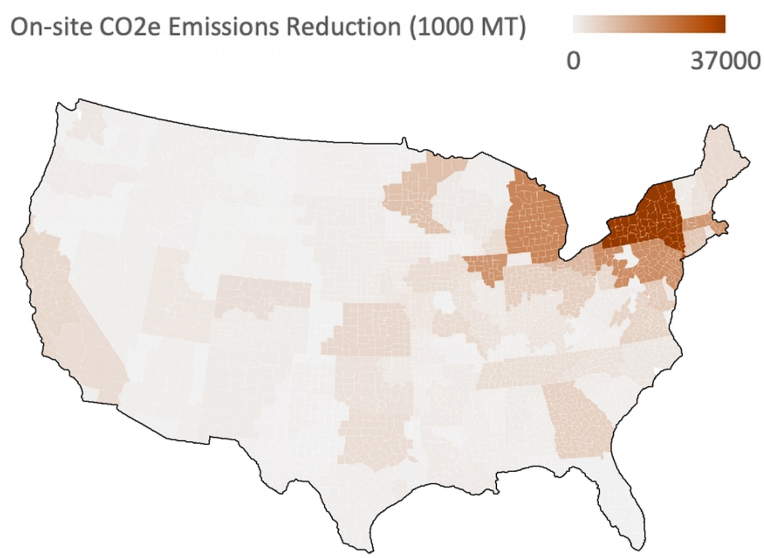
(b)

Figure 3-4. Geospatial representation of the percent changes in (a) building annual electricity consumption and (b) annual on-site carbon emissions (from combustion of fossil fuels for space heating) that would result from retrofitting all appliable existing buildings in 2018 with GHPs (including weatherization in SFHs) in each BA.

Figure 3-5 shows the absolute values of the changes in annual electricity consumption and on-site carbon emissions that would result from the mass deployment of GHPs in each BA. The absolute values of electricity savings are high in the densely populated areas in the southern and western United States, including Florida, Texas, and California. In Figure 3-5, BAs in Maine and Vermont are colored red, indicating an increase in electricity consumption. The increase is caused by the current low percentages of electric heating and low cooling demands in the existing buildings in these BAs. In terms of on-site carbon emissions reduction and site energy savings, BAs in New York and Michigan show the highest values because of the high populations and heating demands in these areas.



(a)



(b)

Figure 3-5. Geospatial representation of the absolute values of changes in (a) annual electricity consumption and (b) annual on-site carbon emissions (from combustion of fossil fuels for space heating) that would result from retrofitting all appliable existing buildings in 2018 with GHPs (including weatherization in SFHs) in each BA.

3.3.2 GHP Impacts in Each BA

Table 3-2 lists the minimum, maximum, and average values of the changes (the absolute values and the percentages) in electricity and fossil fuel consumption, as well as the on-site carbon emissions that result from the GHP retrofits in the 134 BAs. These values represent the maximum energy savings that can be achieved each year compared with the baseline energy consumption of the existing US building stock in 2018, assuming all the applicable existing buildings are retrofitted with GHPs at once. Positive values indicate energy savings or carbon emission reductions compared with the baseline, and negative values indicate increased energy use or carbon emissions.

Table 3-2. Statistics of changes in building energy consumption and on-site emissions resulting from retrofitting all applicable existing buildings in 2018 with GHPs and weatherization in SFHs in each BA

Building energy consumption parameters		Minimum	Maximum	Mean
Building electricity savings	GWh/year	−150.2	27,958	2,992
	%	−2.1	29	17
Natural gas savings	10^6 MMBtu/year	0.02	384	29
	%	1.4	77	62
Heating oil savings	10^6 gal/year	0	758	31
	%	0	100	54
Propane savings	10^6 gal/year	0.15	274	29
	%	1.6	85	56
On-site carbon emissions reduction	10^3 MT/year	16.18	36,560	2,549
	%	1.4	82	57

On-site fossil fuel consumption and associated carbon emissions are reduced in all BAs. Although GHP retrofits result in electricity savings in most BAs, they lead to increased electricity consumption in a few BAs in the Northeast because most space heating in these BAs is provided by furnaces or boilers that consume fossil fuels, and the heating requirements are very large. Replacing these furnaces and boilers with GHPs will increase electricity consumption but will eliminate fossil fuel consumption for space heating. More electricity would be consumed in these BAs if the gas furnaces were replaced with ASHPs because of their lower heating efficiency than GHPs and the usage of supplemental electric resistance heating. In BAs without propane or heating oil consumption, the change in propane or heating oil consumption is zero.

All the graphs and tables in this section come from modeling the changes if all applicable existing buildings in 2018 were retrofitted at once. However, retrofitting all the applicable existing buildings will take many years, so the energy savings and carbon emission reductions that can be achieved each year would be smaller than those presented above.

If GHP deployment increases linearly from 0% in 2021 until reaching its maximum by 2050,[13] cumulatively, $1,020 billion[14] in fuel costs will be saved, and 5,290 MMT equivalent carbon emissions will be avoided by replacing the on-site consumption of fossil fuels for space heating with GHPs and weatherization in SFHs. These numbers are strictly the on-site cost savings and carbon emission reductions that are achieved in the building sector and do not include the fuel cost savings and emission reductions in the electric power sector, which is assessed in Section 4.

[13] This calculation does not account for any new construction between 2021 and 2050.
[14] The cumulative fuel cost is calculated based on AEO-projected fuel prices (USD [2021]) at various regions in the United States. Data source: EIA. 2022. "Table 3. Energy Prices by Sector and Source, Reference Case." *Annual Energy Outlook 2022*, Interactive Table Viewer. https://www.eia.gov/outlooks/aeo/data/browser/.

3.4 DISCUSSION AND LIMITATIONS OF THE CURRENT STUDY

Energy savings from the GHP retrofits result from several causes. First, the higher operational efficiency of the new GHP system is a result of more favorable ground source temperatures than ambient air for the heating and cooling operation of the heat pump. Second, distributed GHP systems modeled in this study avoid the common issue of simultaneous heating and cooling in commercial buildings conditioned with conventional variable air volume systems. Third, fan power is reduced by using fans with higher efficiency and separately controlling the airflow for climate control and OA ventilation (i.e., using a small fan in the DOAS to deliver OA and allowing fans of the GHPs to be turned on and off with the compressor based on the thermal demands). Finally, heating and cooling loads are lowered by reducing air infiltration and ductwork leakage in SFHs.

The limitations in the building energy simulation performed in this study are as follows.

- The prototype building models are based on the 2007 edition of ANSI/ASHRAE/IES Standard 90.1 for commercial buildings and the 2006 edition of IECC for residential buildings. These models are used to represent the average performance of existing buildings.[15] Newer/remodeled buildings may be more efficient, so the energy savings from retrofitting newer buildings may be lower than those calculated in this study. On the other hand, more energy savings may be obtained by retrofitting older buildings. More extensive modeling that accounts for the variances in building energy efficiency is recommended for future studies.

- Newer/remodeled SFHs may have a lower OA infiltration rate than that in the 2006 prototype SFHs, and the energy savings resulting from weatherization may be lower than what is calculated in this study. On the other hand, the energy savings may be higher by weatherizing older (leakier) buildings. More extensive modeling that accounts for the variances in air tightness in SFHs is recommended for future studies.

- TMY3 weather data were used instead of historical weather data in all the simulations of the prototype buildings and the building stock modeling used for generating the original EULPs. The typical weather year represents average weather over the past 30 years, which might not include extreme weather conditions. Therefore, the calculated peak electricity demands in this study are likely lower than in actual years in the future given the continuous climate change. It is thus recommended to consider future year weather data in future studies.

- Fraction factors for HVAC-related site energy consumption resulting from GHP retrofits and weatherization in SFHs were generated using DOE's prototype building models, which have a set of operation schedules for each prototype building. These schedules do not always align with the operation schedule of the building stock models used for generating the original EULPs, which used a series of different operation schedules for each type of the modeled buildings to reflect the diversity of building operation. It may introduce some errors in the calculated energy savings, especially during the shoulder seasons. More extensive modeling that accounts for the variances in operation schedules of different buildings is recommended for future studies.

[15] Less than 17% of existing buildings in 2018 were built after 2007, which are likely more energy efficient than the modeled buildings. On the other hand, many existing buildings built before 2007 may be less efficient than the modeled buildings.

3.5 SUMMARY

The building sector analysis results indicate that retrofitting all applicable buildings existing in 2018 with GHPs and weatherization in SFHs can save 401 TWh of electricity and eliminate 5,138 billion MJ of fossil fuel (e.g., natural gas, heating oil, propane) consumption (approximately 4,747 billion ft^3 of natural gas equivalent) each year compared with the electricity and fuel consumption of the existing building stock in 2018. The reduced on-site fossil fuel consumption at these buildings would avoid 342 MMT of equivalent carbon emissions each year. These benefits result from higher operational efficiency of GHP systems, avoided simultaneous heating and cooling in commercial buildings, reduced fan power due to improved fan efficiency and ventilation control, as well as lowered thermal loads by reducing air infiltration and ductwork leakage in SFHs.

Retrofitting existing HVAC systems with new GHPs and weatherization in SFHs will reduce electricity consumption in most parts of the United States, except in a few regions in the Northeast. Electricity savings are larger in densely populated areas in the southern and western United States. If the retrofits increase linearly from 0% in 2021 to 100% of all applicable buildings in 2050, $1,020 billion in fuel costs will be saved, and 5,290 MMT equivalent carbon emissions will be avoided by replacing the on-site consumptions of fossil fuels for space heating with GHPs and reducing air infiltration and ductwork leakage in SFHs. This estimate does not include the carbon and cost savings realized at the grid level, which are explored in the following sections.

4. ELECTRIC POWER SECTOR ANALYSIS

This section reviews ReEDS and PLEXOS modeling results to analyze the impacts of mass GHP deployment, which includes weatherization in SFHs, on the energy and capacity mix of the contiguous US electric power system. These results also show how the timing and quantity of electric power demand reduction reduces (1) the required transmission expansion for supporting grid decarbonization, (2) costs to the power system as a whole and electricity prices to consumers, and (3) the summer and winter resource adequacy requirement.

This study focuses on identifying the types and magnitudes of benefits resulting from the mass GHP deployment and weatherization in SFHs. The costs of GHP installation and weatherization, which depend on the maturity and size of the industry supporting it, were not considered as part of this study and will be accounted for in a future analysis.

This section first presents the four core scenarios and two sensitivities incorporated into the modeling analysis (Section 4.1) and then discusses the ReEDS and PLEXOS results (Section 4.2), limitations of the study (Section 4.3), and a summary of results (Section 4.4).

4.1 SCENARIOS AND ASSUMPTIONS

4.1.1 Core Scenarios

Four core scenarios were formulated for this study:

- **Base:** In this scenario, there is no GHP deployment, building sector energy consumption is consistent with Annual Energy Outlook (AEO) 2022 projections, and the CO_2 emission policy remains the same as existing state policies, including renewable portfolio standards, clean energy standards, and CO_2 emissions policies.

- **Base + GHP:** In this scenario, the GHP deployment rate increases linearly from 0% in 2021 to 100% in 2050. GHPs are included in new constructions starting in 2022, with the same assumptions as the existing buildings regarding the percentage of buildings applicable for GHPs and the energy savings compared with conventional HVAC systems.[16] The total floor space of new constructions is based on residential and commercial building stock changes[17] predicted by the EIA (AEO 2022).

- **Grid Decarbonization:** In this scenario, the national electric power grid's CO_2 emissions will be reduced by 95% in 2035 and 100% in 2050 as compared with the 2005 level.[18] This reduction indicates that all power generation will use clean energy by 2050.

- **Grid Decarbonization + GHP:** This scenario incorporates the effects of GHP deployment into the decarbonization scenario using the same GHP assumptions as the Base + GHP scenario. Both the grid decarbonization goal and the GHP deployment goal will be achieved in 2050. Avoided end-use emissions from GHP deployment do not count toward the grid decarbonization goal but are accounted for separately in the quantification of economy-wide emission effects.

4.1.2 Electrification Scenarios

In addition to the core scenarios, two electrification scenarios are formulated in this study based on values derived from the *Electrification Futures Study* (EFS, Sun et al. 2020). Both electrification scenarios use the power system decarbonization pathways used by the decarbonization scenarios among the core scenarios.

- **EFS:** No GHP deployment occurs, and economy-wide electrification of end uses—including partial building electrification through air source heat pumps (ASHPs), including the cold climate heat pumps, and other electrified devices for water heating and cooking—occurs, consistent with the values used in the high-electrification scenario from the EFS.[19] Weatherization in SFHs was not included in EFS.

- **EFS + GHP:** An economy-wide electrification of end uses occurs, along with 100% GHP deployment in applicable existing and new buildings coupled with weatherization in SFHs.[20] Electrification of other end uses (not for heating and cooling) is consistent with the values used in the high-electrification scenario from the EFS.

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[16] Energy savings in new constructions are approximately calculated by multiplying the total floor space of applicable new constructions and the normalized energy savings per unit of floor space, which are calculated based on energy savings achieved by GHPs (including weatherization in SFHs) in existing buildings as presented in Section 3.
[17] Building stock changes are modeled using the residential and commercial demand modules of the National Energy Modeling System, with residential building stock measuring the total number of units and commercial building stock measured in terms of total floor space, each broken down into US census regions.
[18] The electric sector CO_2 emission cap is based on the Decarbonization scenario in the Solar Futures Study and is consistent with goals presented in *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (White House 2021).
[19] In the EFS scenario, ASHPs were assumed to be used in 68% of residential buildings and 46% of commercial space in the United States. It is also assumed that residential ASHP efficiency will increase by 116% from 2015 to 2050 in the rapid technology development case.
[20] ASHPs in the EFS scenario are replaced with GHPs.

4.2 ANALYSIS RESULTS

4.2.1 ReEDS Capacity Expansion Modeling Scenario Results

As discussed in Section 2, ReEDS is an open-source capacity expansion modeling tool developed by NREL.[21] It simulates the evolution of the US power system by providing forecasts of new generation resources and transmission lines, as well as accounting for the load growth and retirement of aging infrastructure. This subsection describes ReEDS results of generation portfolios that capture the benefits of deploying GHPs (including weatherization in SFHs) in residential and commercial buildings. The impacts with and without fully decarbonizing the grid are compared. The analysis was completed using a version of the main ReEDS model from the spring of 2022.

4.2.1.1 Generation and Capacity Portfolios

Figure 4-1 shows that in 2050, if there is complete GHP deployment for all applicable residential and commercial buildings—representing 68% of the building stock in 2050—the electric power generation requirement will be reduced by 585 TWh and 593 TWh each year compared with the Base and the Grid Decarbonization scenarios, respectively. The major difference between the Base and the Grid Decarbonization scenarios lies in the types of generation being reduced. In the Base + GHP scenario, energy generation is reduced across all technology types, including fossil and renewable technologies. In contrast, the Grid Decarbonization + GHP scenario shows reductions primarily in variable renewable generation using wind, solar, or other variable renewable energy (VRE) and hydrogen combustion turbines (H_2-CTs), with small increases in output from nuclear power plants and solar photovoltaic (PV) battery hybrid storage plants.

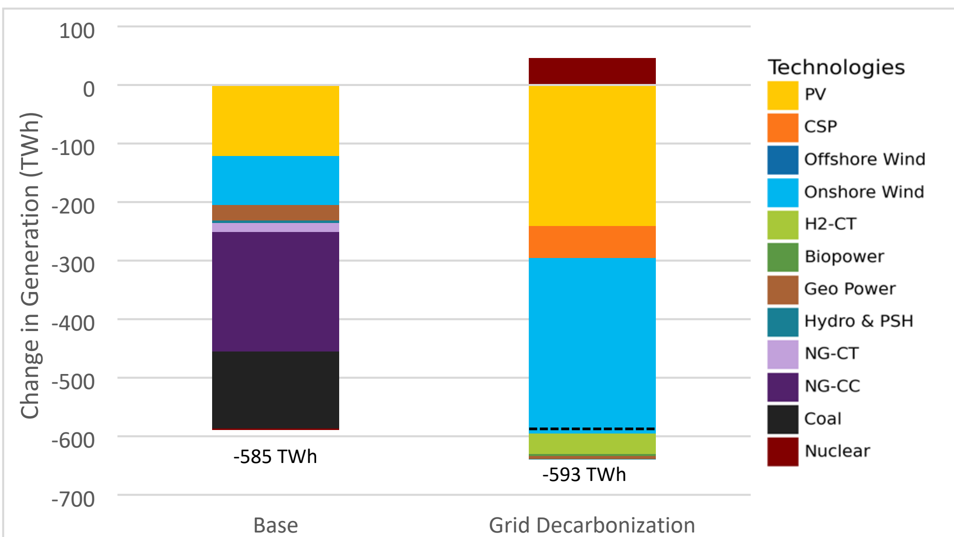


Figure 4-1. Changes in annual national generation (TWh) in 2050 resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Base and Grid Decarbonization scenarios.

Figure 4-2 shows that with GHP deployment in all applicable commercial and residential buildings, a sizeable reduction exists in installed capacity in 2050 compared with the Base and the Grid Decarbonization scenarios. GHP deployment in the Grid Decarbonization scenario doubles the reduction in installed generation and storage capacity compared with that in the Base + GHP scenario (345 GW vs.

[21] For more information, see https://www.nrel.gov/analysis/reeds/.

173 GW). In the Grid Decarbonization scenario, a large fraction (74%–77%) of the generation mix is made up of VRE sources, which typically have lower capacity factors than natural gas which is heavily used in the Base scenario. Therefore, the Grid Decarbonization scenario contains a large fraction of battery storage. These results indicate that GHP deployment will have a greater effect on electric power systems with higher VRE and energy storage deployment.

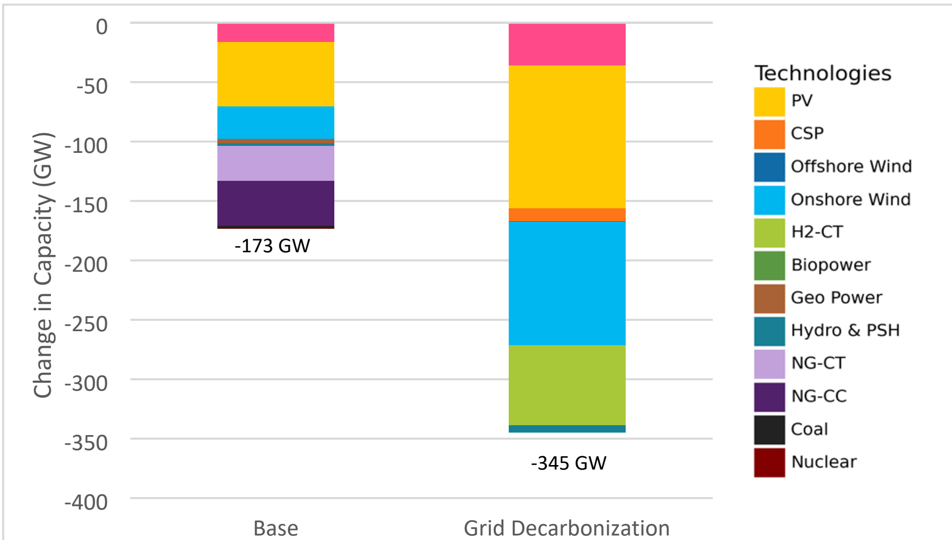


Figure 4-2. Changes in national installed capacity in 2050 (GW) resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Base and Grid Decarbonization scenarios.

4.2.1.2 Interregional Transmission Expansion Requirement

The interregional transmission expansion results are shown in Figure 4-3. The mass GHP deployment in the Base and the Grid Decarbonization scenarios reduces the need for transmission additions. Similar to the generation capacity changes, a greater benefit of avoided transmission additions can be achieved by deploying GHPs in the Grid Decarbonization scenario than in the Base scenario. In the Grid Decarbonization scenario, the electric power system transitions to a high-VRE system, which benefits from increased transmission additions to connect load centers and to provide geographic diversity of generation and load. The mass GHP deployment can reduce the new transmission requirement by 3.3 TW·mi, or a 17.4% reduction, in the Base scenario and 36.7 TW·mi, or 33.4% reduction, in the Grid Decarbonization scenario. With a representative transmission expansion of 1,500 MW capacity per transmission line, the 36.7 TW·mi reduction could represent on the order of 24,500 mi of avoided transmission construction.

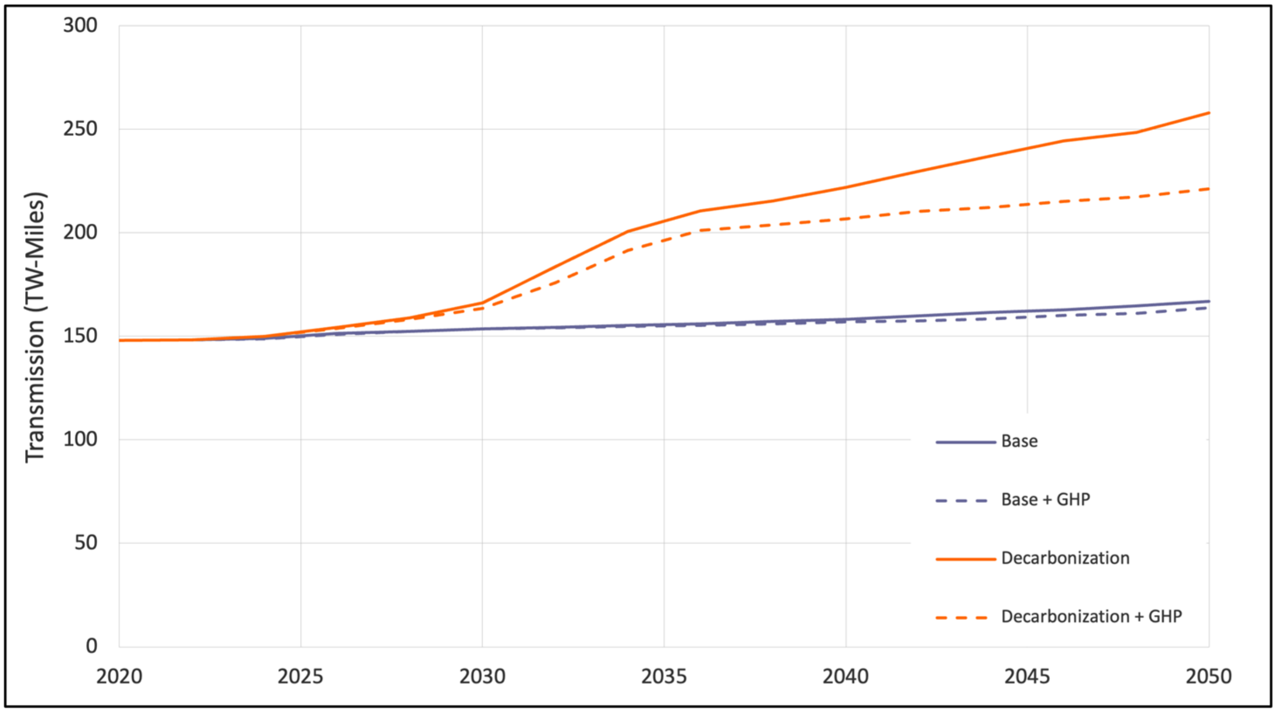


Figure 4-3. Interregional transmission expansion requirements in the Base and Grid Decarbonization scenarios with and without deploying GHPs into residential and commercial buildings in the United States (including weatherization in single-family homes) from 2022 to 2050.

Table 4-1. Interregional transmission expansion results comparison

Scenario		New + existing transmission in 2050 (TW·mi)	New transmission in 2050 (TW·mi)	Reduction (TW·mi)	Reduction (%)	Present value of transmission capital cost savings from 2022 to 2050 ($ billions)
Base	No GHP	167.0	19.0	—	—	—
	With GHP	163.7	15.7	3.3	17.4	2.7
Grid Decarbonization	No GHP	257.9	109.9	—	—	—
	With GHP	221.2	73.2	36.7	33.4	29.9

Reduced transmission has two effects: cost savings and ease of implementation. The total system cost savings in terms of the present value (5% discount rate) in the long-distance transmission system from the deployment of GHPs is $2.7 billion in the Base scenario and $29.9 billion in the Grid Decarbonization scenario. Transmission costs, including capital and operation and maintenance (O&M), account for 10% of total grid costs. Although GHP deployment reduces the requirement for new transmission construction and the associated costs, the transmission cost savings represent only approximately 1% of the total electricity payment reduction between 2022 and 2050. In recent years, there has been greater difficulty in permitting and constructing new transmissions. Therefore, reducing the amount of high-voltage transmissions may have benefits beyond cost savings by reducing the uncertainty and delays of getting new transmissions constructed to serve the needs of a decarbonized grid. It also reduces land use impacted by the transmission expansion.

4.2.1.3 Resource Adequacy

Resource adequacy (RA) is an important criterion for planning and operating electric power systems. Sufficient RA is required to meet the supply- and demand-side electric demands without a shortfall. Consumption and generation must be precisely balanced at all times; shortfalls in energy can result in blackouts. North American Electric Reliability Corporation (NERC) guidance sets a standard that power systems should procure sufficient eligible capacity such that there should be less than 1 day of shortfall in 10 years. The capacity that contributes to RA differs from the installed capacity discussed in the previous subsection in that it represents the portion of a generator or storage resources capacity that can be used during a reliability event. The amount of capacity that can contribute toward RA varies depending on the type of supply and the timing of reliability events. Although most regions currently experience peak and net peak demands in the summer, electrification (especially in buildings) can create more winter-peaking regions. The 100% Clean Electricity by 2035 Study (Denholm et al. 2022) contained electrification scenarios assuming completely electrified residential and commercial space heating without using GHPs (assumed electrification with ASHPs supplemented with electric resistance heaters) and observed winter peaks 35% higher than summer peaks. This transition from summer peak to winter peak is not included in the Base and Grid Decarbonization scenarios (with and without GHPs), but it is partially modeled in this study's EFS scenario (see Section 4.2.1.7).

ReEDS models RA and ensures that planning reserve margins comply with published NERC values for the peak demand and available capacity that can contribute toward RA in each season. Technologies are assigned a capacity credit, which represents the availability of a technology to produce power during a reliability event. For example, conventional nonvariable generation resources have a capacity credit of one. For VRE, a seasonal capacity credit is calculated by using the net hourly load duration curve to approximate the expected load-carrying capacity. This method captures the variability in weather, as well as the geographic correlation in resources that affect a VRE's ability to contribute capacity toward RA. Storage capacity credit is calculated by simulating hourly storage dispatch for each region and storage configuration. Further details on the calculation of capacity credit are available in ReEDS documentation (Ho et al. 2021). In the modeled core scenarios, only the summer season was a binding requirement for RA, and the other seasons' resources were in excess of the established planning reserve margin. This section focuses on changes occurring during the summer season because it is the driving factor in system investment decisions.

Figure 4-4 demonstrates the annual difference in 2050 summer RA eligible capacity resulting from the mass GHP deployment in the Base and the Grid Decarbonization scenarios. The summer RA eligible capacity requirement is reduced by 102 GW after deploying GHPs in the Base or the Grid Decarbonization scenario. However, the makeup of the reductions differs substantially between the two scenarios, reflecting the types of resources built primarily for satisfying RA rather than energy. In the Base scenario, most reductions come from natural gas combustion turbines and combined cycle plants, with the next-largest fraction coming from battery storage. In the Grid Decarbonization scenario, with all CO_2-emitting power plants retired by 2050, the largest contributor to the summer RA eligible capacity requirement reduction comes from H_2-CT. There is a similar reduction in battery storage capacity in the Base and Grid Decarbonization scenarios, with both seeing reductions in 6 and 8 h duration batteries. The Grid Decarbonization + GHP scenario has a greater reduction in solar RA eligible capacity, primarily because of the larger share of PV battery hybrid plants, which maintain a higher capacity credit under high-VRE scenarios compared with traditional PV plants.

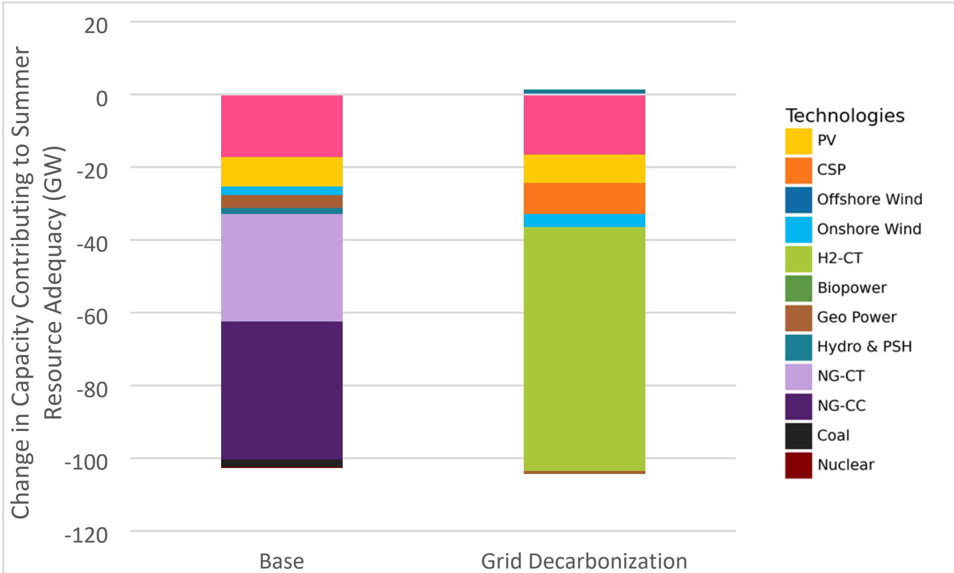


Figure 4-4. Changes in 2050 summer RA eligible capacity in the Base and the Grid Decarbonization scenarios resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes.

The noncoincident peak demands of the studied four core scenarios are listed in Table 4-2. To ensure sufficient capacity for RA, a planning reserve margin applied to each region, the summation of the regional seasonal peak demand, or noncoincident peak, is closely related to this requirement. Although spatially correlated, the exact day and hour on which peak demand occurs in each region varies, and a noncoincident peak will exceed the national coincident peak, which is the maximum demand nationally occurring at a specific day and hour. The total noncoincident peak demand in 2022 is 650 GW and will be used as a reference to analyze the peak demand growth. As shown in Table 4-2, in both the Base and the Grid Decarbonization scenarios, the mass deployment of GHPs (including weatherization in SFHs) will significantly reduce the national noncoincident peak demand in 2050. This result means by adopting the GHP technology, much less new generation capacity is needed to meet the electricity demand and to address RA needs. In other words, the expansion investment of both generating units and transmission lines can be relieved with the mass GHP deployment, which has already been validated in the capacity mix analysis and transmission expansion requirement analysis. Of note in the Grid Decarbonization + GHP scenario, reductions in H_2-CT would also reduce the investments in pipelines, storage, and hydrogen production facilities that are needed to support green hydrogen.

Table 4-2. Noncoincident peak demand comparison between 2022 and 2050 for four core scenarios

Year and case		Noncoincident peak demand (GW)	Increase from 2022 (%)
2022		650	—
2050	Base	839	29.0
	Base + GHP	697	7.2
	Grid Decarbonization	841	29.3
	Grid Decarbonization + GHP	700	7.7

4.2.1.4 CO_2 Emissions

The CO_2 emissions in this section are reported in million metric tons (MMT) of emitted CO_2 instead of the CO_2e used in Section 3. The CO_2 measures the total combustion emissions, and CO_2e includes additional GHG effects associated with a specific fuel (e.g., pipeline leakage in natural gas distribution). The CO_2 emissions were focused on in this section because the implemented decarbonization policy is a cap on those emissions and not CO_2e, mirroring the scope of CO_2 policies such as the Regional Greenhouse Gas Initiative.

The electric sector CO_2 emissions are shown in Figure 4-5. In the Base + GHP scenario (dashed-blue line), the deployment of GHP will lead to a reduction in CO_2 emissions, relative to a no-deployment Base scenario (solid blue line), because the total electric load (TWh) and peak demand (GW) are both smaller with GHP deployment by 2050, resulting in a 217 MMT/year reduction by 2050. However, the emission of the Grid Decarbonization scenario (solid orange line) is identical to that of the Grid Decarbonization + GHP scenario (dashed orange line). This result is because in the Grid Decarbonization scenario, the carbon emission constraint is always binding because of the rapid 95% electric power system decarbonization target in 2035 and complete decarbonization in 2050. GHP deployment rates assumed in this study are not aggressive enough to alter the power generation emissions.

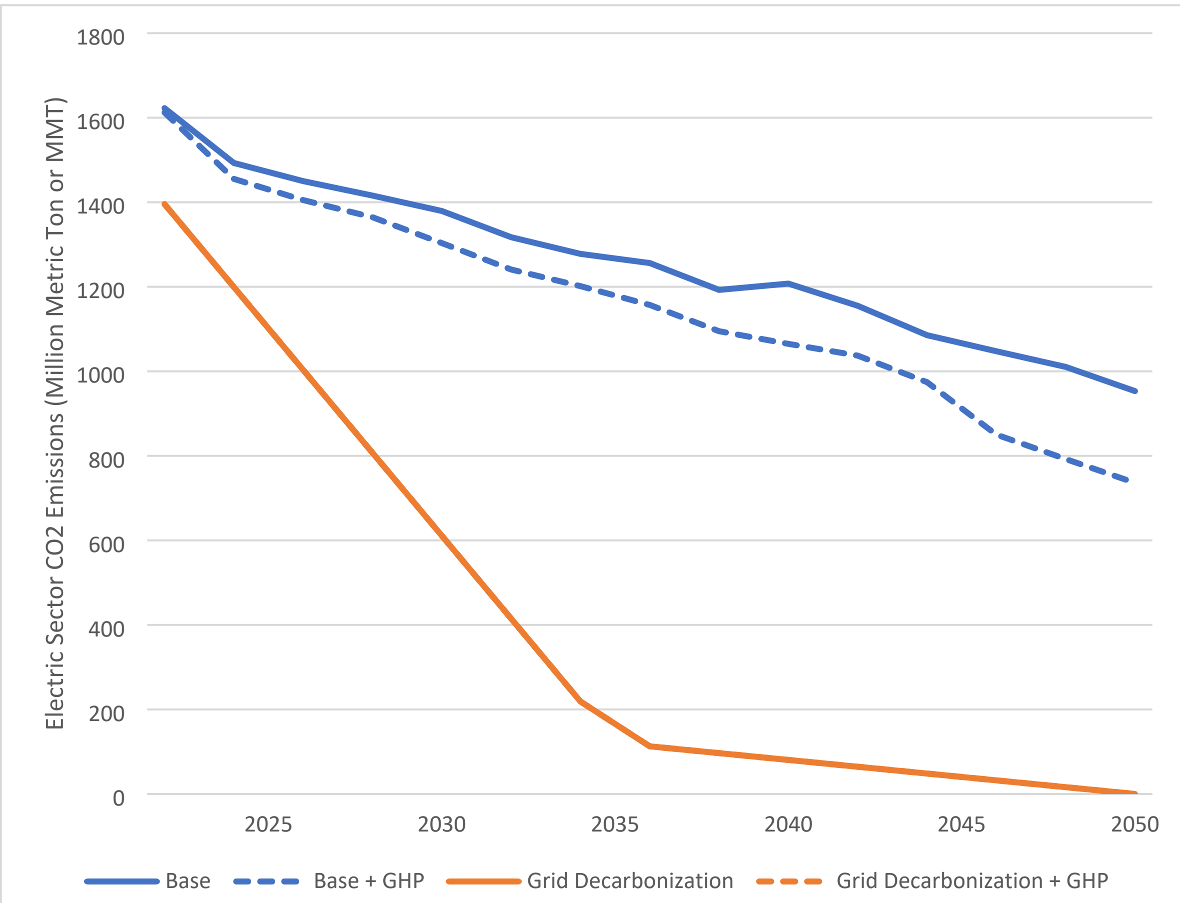


Figure 4-5. Electric sector CO_2 emissions in four core scenarios from 2022 to 2050. Note that the Grid Decarbonization + GHP scenario has identical emissions as the Grid Decarbonization scenario.

In addition to reducing electric power systems' emissions as shown in Figure 4-5, GHPs also displace end-use heating fuels such as natural gas and heating oil. Combined electric and building sector emissions are analyzed in this subsection. Figure 4-6 illustrates the combined electric and building sectors emissions for the four core scenarios from 2022 to 2050. In contrast to the electric sector–only emission scenarios, GHP deployment measurably diverges from the no-deployment counterparts. The increase in the combined electric and building sectors emissions following 2035 in the Grid Decarbonization scenario is a result of the decarbonization policy being applied solely to electric power emissions. The remaining 5% of electric power emission reductions are offset by increases in emissions in buildings. The amount of avoided end-use emissions from deployment of GHPs (including weatherization in SFHs) is sufficient, if credited, to help achieve the net-zero emissions goal of the electric power system by 2035.

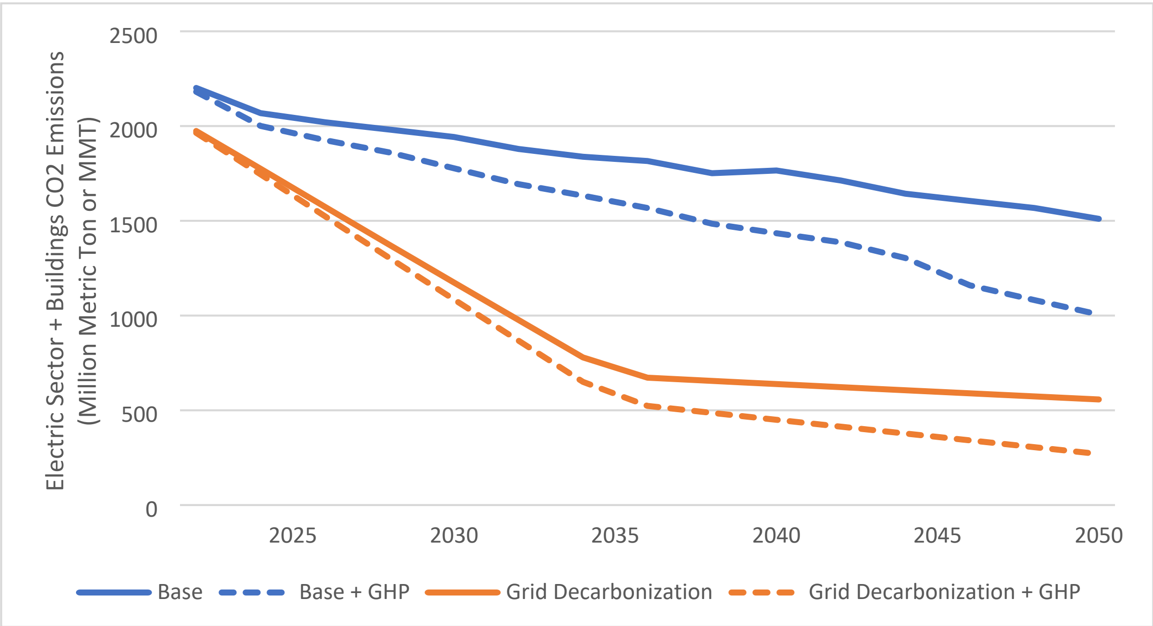


Figure 4-6. Combined electric and building sectors CO_2 emissions with and without GHP deployment (including weatherization in SFHs) in the Base and the Grid Decarbonization scenarios from 2022 to 2050.

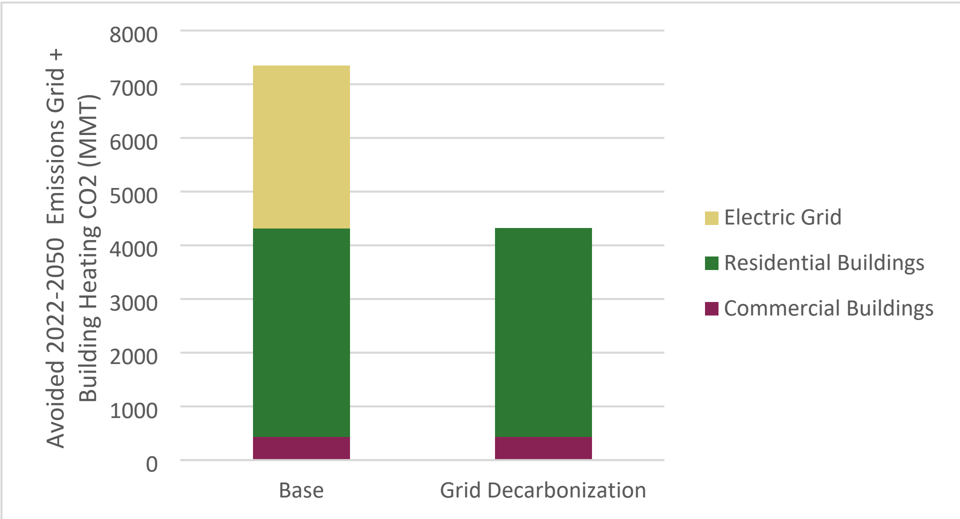


Figure 4-7 shows the cumulative CO_2 emission reductions in the combined electric and building sectors from 2022 to 2050 resulting from 100% GHP deployment in all applicable buildings for the Base and the

Grid Decarbonization scenarios. The avoided end-use heating CO_2 emission from GHPs are still counted toward the combined electric and building sectors CO_2 emission. In the Base scenario, the deployment of GHP will contribute 7,351 MMT CO_2 emission reduction in total, where 3,033 MMT comes from electric sector, and the balance of 4,318 MMT comes from the reduction of on-site fossil fuel combustion for space heating in the building sector. In the Grid Decarbonization scenario, the deployment of GHPs primarily reduces the end-use CO_2 emission at buildings by 4,320 MMT from 2022 to 2050, with small and unreported CO_2 emission reduction from the electric sector.

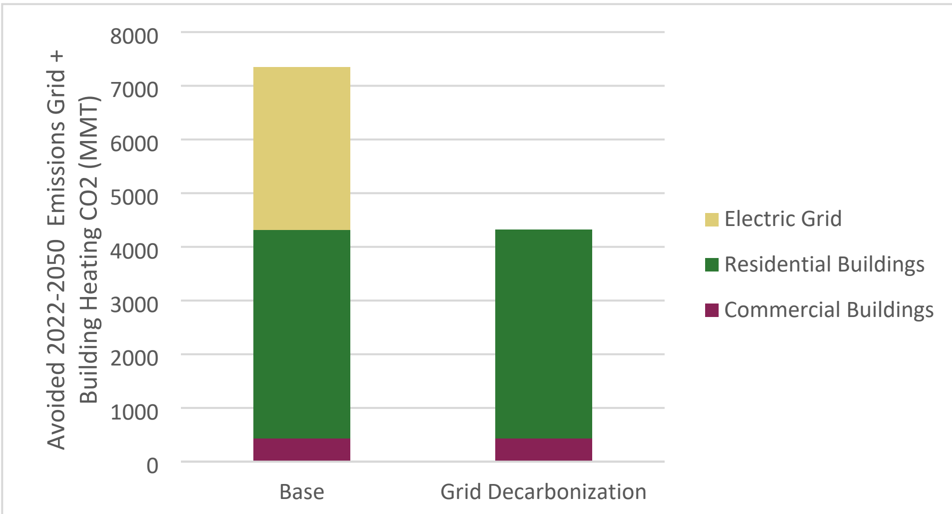


Figure 4-7. Cumulative combined electric and building sectors CO_2 emission reduction from 2022 to 2050 resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Base and the Grid Decarbonization scenarios.

4.2.1.5 Marginal System Cost of Electricity

The national-average marginal system cost of electricity from 2022 to 2050 is shown in Figure 4-8 for the Base and the Grid Decarbonization scenarios with and without GHP deployment. The marginal system cost is composed of the locational marginal price of electricity, the marginal price of capacity for the planning reserves, the marginal price of operating reserves, and the marginal credit price of renewable portfolio standards.[22] The national-average marginal system cost of electricity in 2050 is listed in Table 4-3 along with the predicted total savings in electricity payments by consumers resulting from the mass GHP deployment in the two scenarios for 2050 and the cumulative savings from 2022 to 2050.

As expected, the marginal system cost of electricity is much higher for the Grid Decarbonization scenarios than the Base scenarios because of the replacement of existing fossil-fired power plants with zero-CO_2 power plants to achieve 100% grid decarbonization. Investment in VRE substantially increases with grid decarbonization, as does long-distance transmission construction to support the geographic diversity of the VRE resources. The ability for VRE to contribute to resource adequacy declines; therefore, energy storage and expensive power plants (i.e., H_2-CTs) are needed to ensure resource adequacy. New capital expenditures, even for resources with zero operational costs, increase the system

[22] The locational marginal price of electricity, or *energy price*, is most analogous to the PLEXOS electricity price discussed in Section 4.3 but will differ because PLEXOS can capture more extreme prices in its hourly representation compared with the 17 time-slice representation used in ReEDS. The additional temporal granularity and inclusion of generator unit commitment that are accounted for in PLEXOS reflects a greater degree of operational inflexibility, which can result in higher electric power prices compared with that predicted with ReEDS, which is a capacity expansion model.

cost of electricity, which must be recovered through electric rate payers or, in the case of tax incentives, the government.

The reduction in peak demand and flattening of annual energy use resulting from the mass GHP deployment (including weatherization in SFHs) lowers the marginal system cost in both the Base and the Grid Decarbonization scenarios relative to the non-GHP scenarios. The Base scenario makes use of the existing natural gas and coal plants, many of which have already recovered their initial investment cost, resulting in comparatively small cost savings. The reductions in capacity investment, fuel, and O&M costs create a consistent but small change (a 6% decrease) in the marginal system cost of electricity in the Base + GHP scenario in 2050.

With Grid Decarbonization, the marginal system cost of electricity attains a $10/MWh differential by 2036. By 2050, the GHP deployment has reduced the cost for transitioning the existing grid to a decarbonized grid by approximately 30%. This greater reduction in the marginal system cost is explained by the types of capacity and generation changes that occur in the Grid Decarbonization scenarios. To meet 100% grid decarbonization, there is a greater investment in new carbon-free generation and storage, which displaces existing CO_2-emitting generation that has been paid for. The deployment of GHPs reduces the new investment required to meet capacity and energy needs, yielding a greater savings in marginal system cost than in the Base + GHP scenario. The calculated annual (2050) and cumulative (from 2022 to 2050) savings in electricity payments by consumers are presented in Table 4-3.

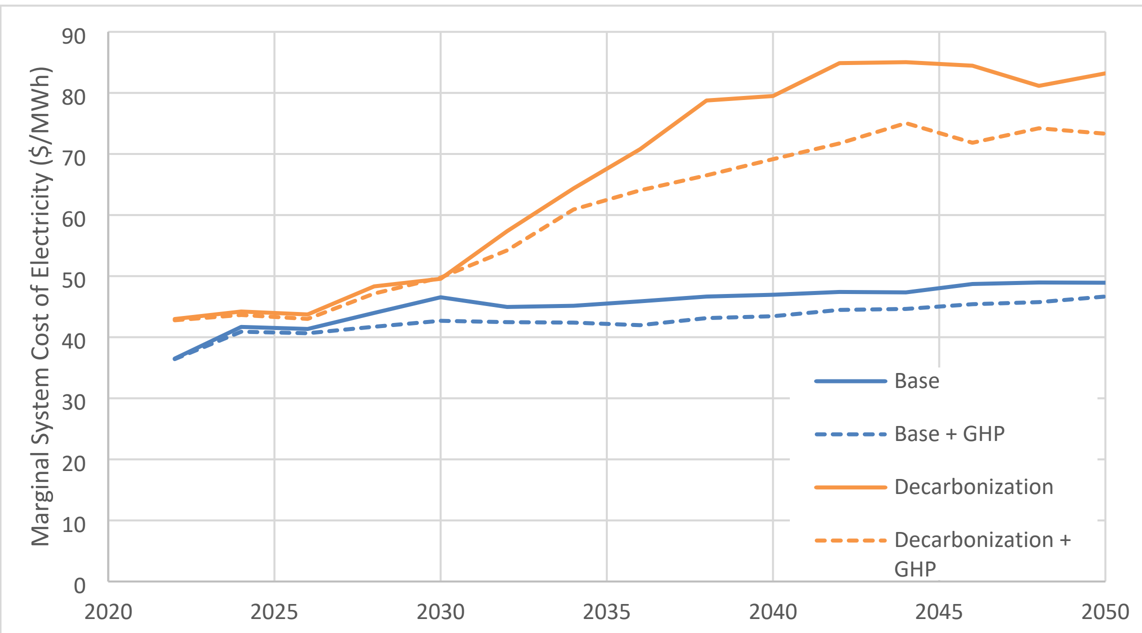


Figure 4-8. National-average marginal system cost of electricity from 2022 to 2050 with and without GHP deployment (including weatherization in SFHs) in the Base and the Grid Decarbonization scenarios.

Table 4-3. Comparison of marginal system cost of electricity and electricity payments by consumers in 2050 and from 2022 to 2050 with and without GHP deployment (including weatherization in SFHs) in the Base and the Grid Decarbonization scenarios

Scenario	Marginal cost ($/MWh)	2050 values of annual electricity payments ($ billions)	Present value of cumulative electricity payments from 2022 to 2050 ($ billions)

No GHP	Base	49	—	257	—	3,206	—
	Grid Decarbonization	83	—	437	—	4,444	—
With GHP	—	—	**Savings ($/MWh)**	—	**Savings ($ billions)**	—	**Savings ($ billions)**
	Base	46	**3**	218	**39**	2,877	**329**
	Grid Decarbonization	73	**10**	342	**95**	3,862	**582**

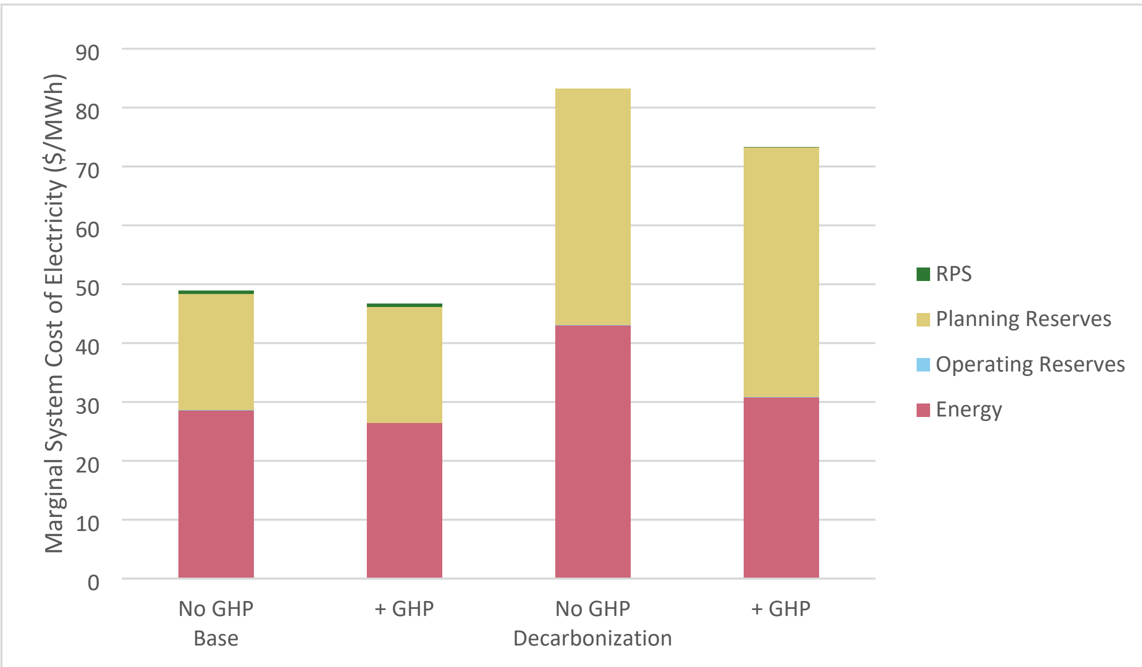


Figure 4-9 shows the breakdown of the marginal system cost of electricity in the four core scenarios in 2050. As shown in this figure, the electricity price mainly consists of the energy price (red bar) and planning reserve price (yellow bar). In the Grid Decarbonization scenarios with and without GHP, the planning reserve price has a larger share because more firm generation capacity needs to be developed to support a high-VRE system while retiring existing natural gas and coal power plants.

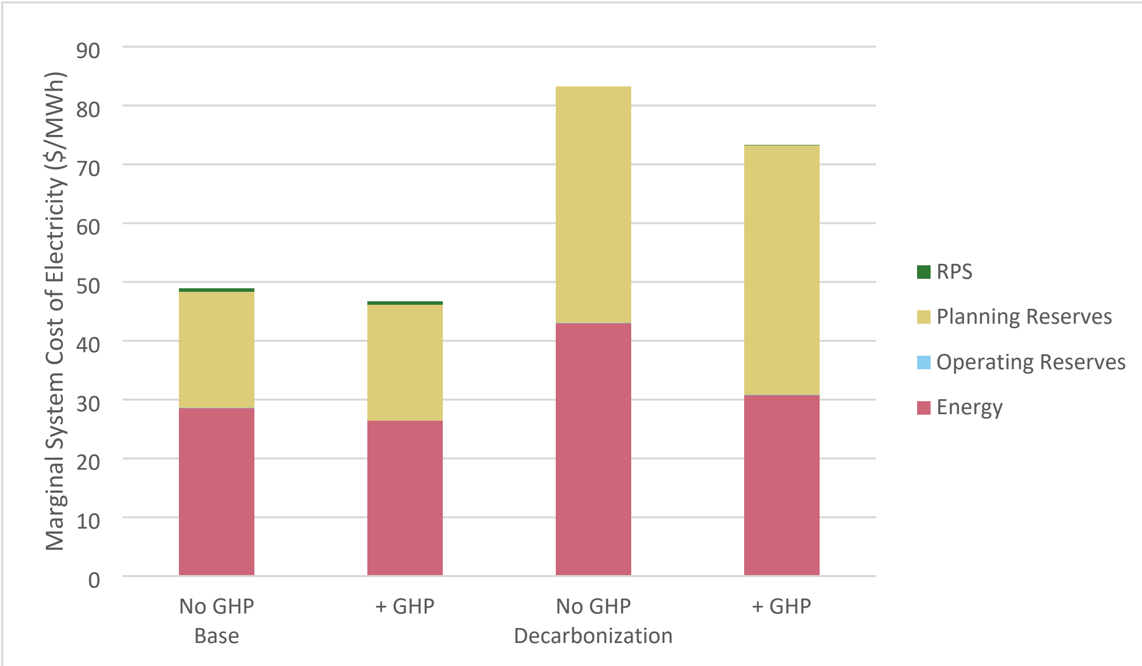


Figure 4-9. Breakdown of the marginal system cost of electricity in 2050 with and without GHP deployment (including weatherization in SFHs) in the Base and the Grid Decarbonization scenarios.

4.2.1.6 System Costs and Benefits

The total cumulative discounted system costs of the four core scenarios are shown in Figure 4-10. The values shown are the present value of the cumulative power system costs (from 2022 to 2050 with 5% discount rate). The metric is related to the marginal system cost of electricity described in the prior section, which characterized the types of services and prices that consumers of electricity would pay to generators and grid operators; the cumulative system cost captures the total costs of investment and operations to electric power generators and grid operators. The system cost is a holistic measure to assess effects of the mass GHP deployment on the electric power system and can be broken down by distinct categories of expense, including capital costs for generation, storage, and transmission, as well as operational costs, including fuel and O&M. Avoided costs outside of the electric power system are not included in this calculation, including changes in building fuel costs.

In the Base and the Grid Decarbonization scenarios, the deployment of GHP technology reduces the total system cost. The total system cost savings are $145 billion and $241 billion in the Base + GHP scenario and the Grid Decarbonization + GHP scenario, respectively. As a percentage, these savings are a 5.1% reduction in the Base + GHP scenario and a 7.2% reduction in the Grid Decarbonization + GHP scenario. The higher cost reduction with GHP in the Grid Decarbonization + GHP scenario is primarily due to greater savings in generation capital costs and transmission investment compared with the changes seen in the Base + GHP scenario.

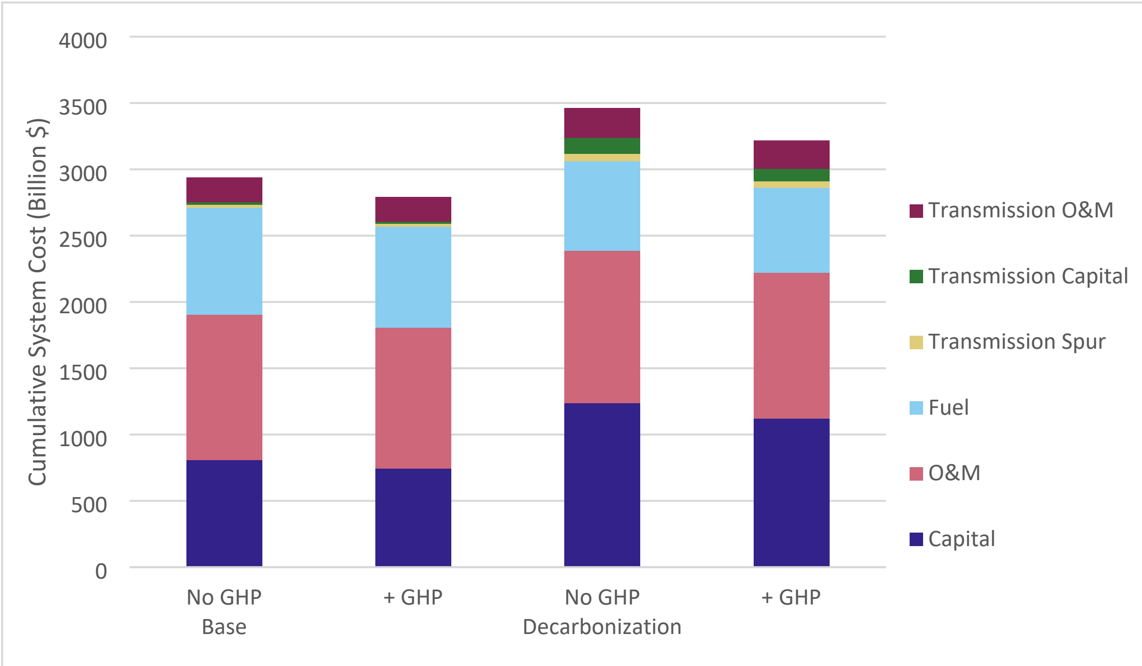


Figure 4-10. Cumulative discounted system cost (2022 to 2050 with 5% discount rate) with and without GHP deployment (including weatherization in SFHs) in the Base and the Grid Decarbonization scenarios.

4.2.1.7 Electrification Sensitivity

The EFS scenario, analyzed in this subsection, considers the electrification of other sectors such as transportation. The EFS scenario also incorporates the Grid Decarbonization assumptions (i.e., reduce emissions by 95% in 2035 and 100% in 2050). Electrification potentials in the original EFS were calculated using the EnergyPATHWAYS model, which is a bottom-up energy sector tool that measures changes to the end-use technology based upon regional stock changes and prescribed assumptions about change to market share of end use technologies. In the EFS high-electrification scenario, ASHPs will be installed in 68% and 46%, respectively, of all residential and commercial buildings existing in 2050. The underlying assumptions achieve only partial electrification of heating and cooling in residential and commercial buildings. Electric demands increase in the EFS scenarios as transportation, industry, residential, and commercial energy uses that were previously met with fuels are electrified. Therefore, the total installed electric power generation capacity in the EFS scenario is much larger than the Grid Decarbonization scenario, with an increase of 1,090 GW in capacity and 1,900 TWh in annual generation.

For this analysis, the high-electrification scenario from EFS was first modified to remove changes in electricity use for heating and cooling in residential and commercial buildings (i.e., without electrification in heating and cooling). Then, GHP deployment in all applicable buildings (78% of residential buildings and 43% of commercial buildings) was applied consistent with the methodology used in the core scenarios. This method created a new electrification scenario that is consistent with the high-electrification scenario of EFS but uses GHP deployment (including weatherization in SFHs) for electrifying residential and commercial heating and cooling. The changes in generation capacity mix and the annual electricity generation in 2050 in the EFS scenario resulting from the mass GHP deployment is presented in Figure 4-11. Electrifying building space heating and cooling with GHPs, along with weatherization in SFHs, reduces electricity capacity and generation requirements by 410 GW and 937 TWh, respectively, compared with the original EFS scenario with high electrification.

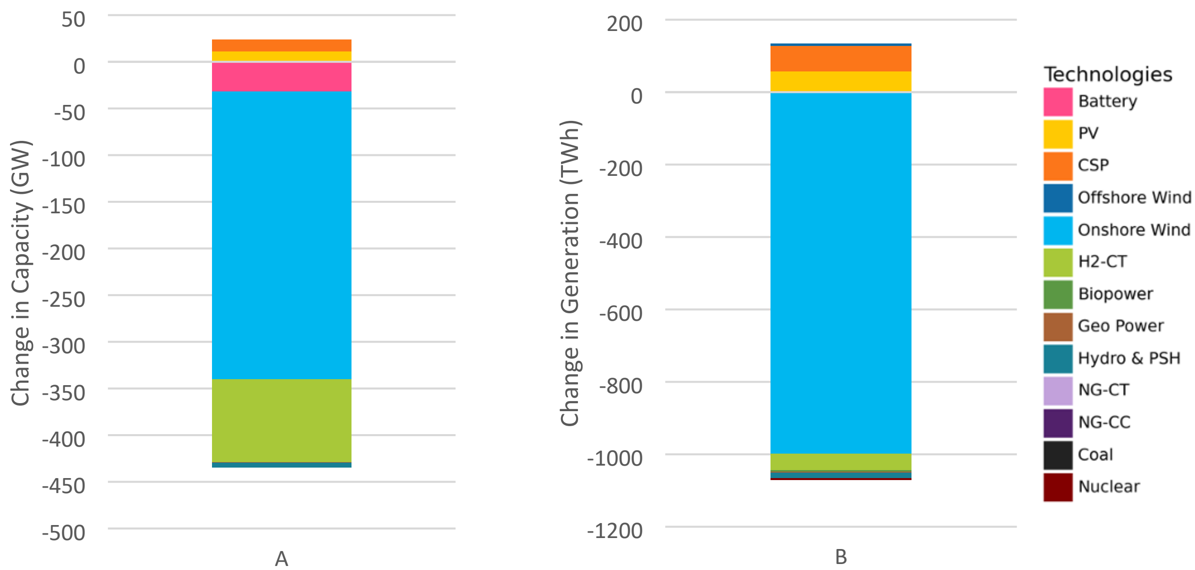


Figure 4-11. Change in (A) national electricity generation capacity and (B) national annual electricity generation in the EFS scenario in 2050 resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes.

Compared with the core scenarios, the mass GHP deployment in the EFS has an increased ability to reduce resource adequacy requirements in cold climate regions, which previously relied heavily on natural gas for heating. This effect would be greater if the original EFS had fully electrified heating and cooling, as was studied in *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* (Denholm et al. 2022). The change in seasonal RA eligible capacity contributions toward the planning reserve margin is shown in Figure 4-12. In contrast to the capacity changes shown in Figure 4-11, bulk reductions in RA eligible capacity are from H_2-CT and battery storage. It can also be observed that RA eligible capacity from solar (PV and CSP) increases in summer while hydropower (hydropower and PSH) increases in winter, which is thought to be due to the wide geographic coverage of GHP applications so that more renewable energy can be accessed. The GHP deployment in the EFS scenario shows a higher reduction in winter peak resource adequacy requirements than in summer, which has increasing importance in EFS, where electrification of heating with ASHPs results in an increasing number of regions shifting from summer peaking to winter peaking.

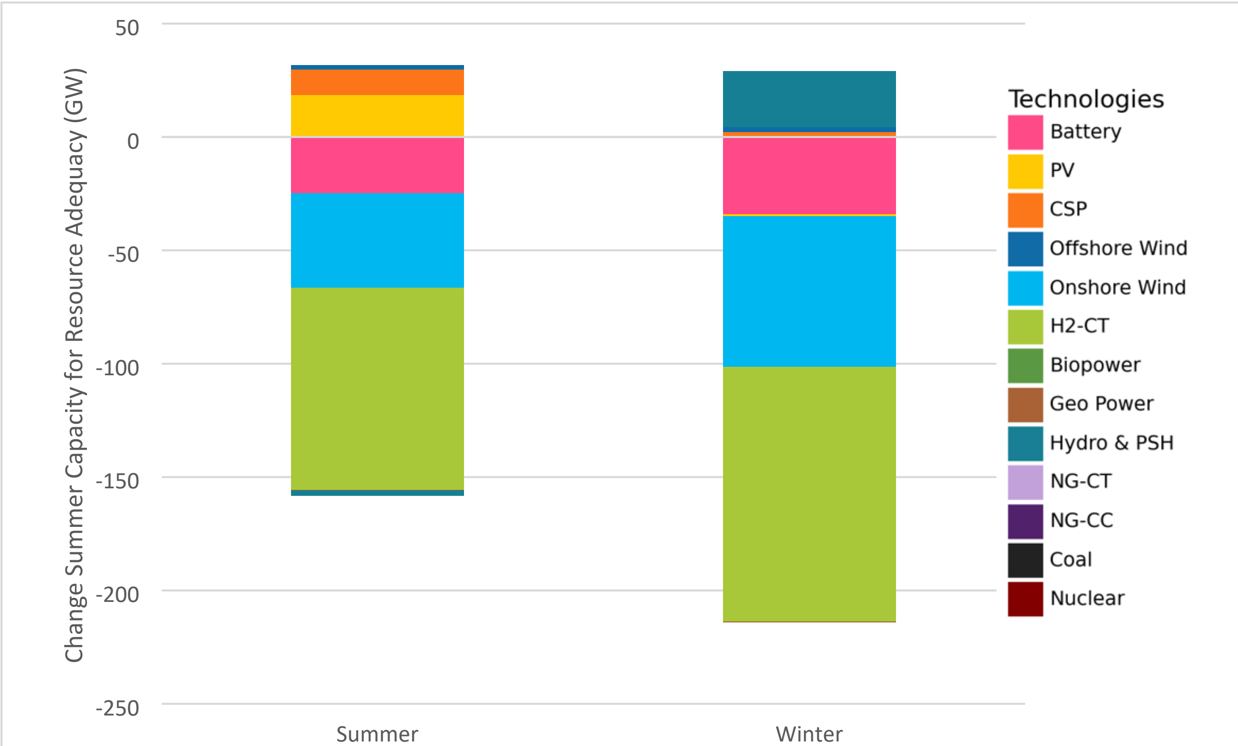


Figure 4-12. Change in summer and winter RA eligible capacity contribution by technologies in the EFS scenario resulting from the mass GHP deployment (including weatherization in SFHs) instead of the partial electrification using ASHPs.

Interregional transmission has a greater buildout in the EFS scenario compared with the core scenarios because of the high deployment of VRE. As shown in Table 4-4, with GHP deployment, interregional transmission is reduced by 65.4 TW·mi, representing a 38% reduction (or $39.5 billion less cost in present value) in new investments. The EFS scenarios directly compared two solutions for electrifying building heating and cooling. The higher efficiency of GHPs relative to ASHPs results in a larger impact relative to the Grid Decarbonization scenarios (see Table 4-4), reducing required transmission expansion by a factor of 1.8 and the present value costs by a factor of 1.3. The comparably lesser effect on the present value costs is a result of the timing of EFS transmission investments, which diverges from the Grid Decarbonization scenarios after 2035.

Table 4-5. Comparison of the interregional transmission expansion requirements in the EFS scenario with and without GHP deployment (including weatherization in SFHs)

Scenario	New + existing transmission in 2050 (TW·mi)	New transmission in 2050 (TW·mi)	Reduction (TW·mi)	Reduction (%)	Present value of transmission capital cost savings with 5% discount rate ($ billions)
No GHP	322	174	—	—	—
With GHP	256	108	65.4	37.7	39.5

Table 4-5 lists the economy-wide emissions in all analyzed scenarios from 2022 to 2050 with and without GHP deployment, respectively. The EFS scenarios show a comparably smaller reduction in economy-wide emissions with GHPs. This result is because the EFS scenario has reduced economy-wide emissions compared with the Base and the Grid Decarbonization scenarios through electrification of both the electric and building sectors.

Table 4-5. Comparison of economy-wide CO_2 emissions in the Base, Grid Decarbonization, and EFS scenarios with and without GHP deployment (including weatherization in SFHs)

Scenario		Economy-wide emissions in 2050 (MMT)		Cumulative emissions from 2022 to 2050 (MMT)	
No GHP	Base	4,529		136,063	
	Grid Decarbonization	3,576		111,129	
	EFS	2,284		94,737	
			Difference		Difference
With GHP	Base	4,024	505	128,712	7,351
	Grid Decarbonization	3,288	288	106,811	4,318
	EFS	2,153	131	92,559	2,178

4.2.2 Detailed Scenario Analysis in 2050 with PLEXOS

Hourly simulation of the electric power system in 2050, which was identified with the capacity expansion modeling (CEM) using ReEDS, was performed with PLEXOS to conduct production cost modeling (PCM) for the four core scenarios discussed in the preceding subsections. PLEXOS results provide a more granular understanding of GHP impacts on the electric power system. In contrast to CEM, PCM provides a higher degree of temporal granularity and includes operational constraints such as unit commitment, ramp rates, and up times of electricity generation. PCM results complement CEM analysis by identifying additional details that are otherwise simplified in the CEM and by providing validation of the operability of an electric power system identified by CEM. The PLEXOS results regarding the grid operations are analyzed in this subsection. The terms in this subsection are explained in the nomenclature page at the beginning of this report.

4.2.2.1 Validation of CEM Results of ReEDS

Sufficient resource adequacy should be provided in an electric power system to minimize the unserved demand, which could result in blackouts or brownouts. The electric demand change resulting from the mass GHP deployment is substantial and it merits a validation of the electric power system identified with CEM results of ReEDS. The validation is performed by comparing key results determined with ReEDS and PLEXOS, respectively.

PLEXOS can allow the load to go unserved if the demand required cannot be met with the available generation, storage, and transmission capacity. An unserved load incurs a significant penalty cost and is used by the model as a last resort. Significant quantities of unserved loads would be a key indicator that the capacity expansion solution determined by ReEDS is underbuilt for the simulation year.

In the findings for all four core scenarios, shown in Table 4- and Table 4-, minimal unserved loads were found, indicating that the capacity expansion solution is sufficient. In the Base and the Grid Decarbonization scenarios without GHP deployment, there are 4 and 9 GWh of annual unserved load, respectively. However, no unserved load was observed in these scenarios if GHPs were deployed.

Table 4- and Table 4- summarize the key metrics reported by PLEXOS for the Base scenario and the Grid Decarbonization scenario, respectively, with and without GHP deployment. Some of these metrics, including power generation capacity and battery energy capacity, directly reflect ReEDS results and they were used to confirm that the electric power system modeled with PLEXOS is an accurate translation from the capacity expansion solution determined by ReEDS. Also included in these tables are metrics that capture operational results that are not reported directly by ReEDS.

Table 4-6. PLEXOS results for the Base scenario with and without GHP deployment (including weatherization in SFHs) in 2050

	Base	Base + GHP	Reduction	Reduction ratio (%)
Annual load (TWh)	5,709	5,091	618	10.8
Annual generator revenue ($ billions)	182	125	57	31.5
Annual average wholesale electricity price ($/MWh)	32	24	8	23.2
Annual operating reserve provision (TWh)	457	413	44	9.5
Annual unserved load (GWh)	4	0	4	100.0
Annual peak demand (GW)	963	839	124	12.9
Generation power capacity (GW)	1,855	1,677	178	9.6
Battery energy capacity (GWh)	3,036	2,626	410	13.5

Table 4-7. PLEXOS results for the Grid Decarbonization scenario with and without GHP deployment (including weatherization in SFHs) in 2050

	Grid Decarb	Grid Decarb + GHP	Reduction	Reduction ratio (%)
Annual load (TWh)	5,709	5,092	617	10.8
Annual generator revenue ($ billions)	771	572	199	25.9
Annual average wholesale electricity price ($/MWh)	135	112	23	16.9
Annual operating reserve provision (TWh)	673	584	89	13.3
Annual unserved load (GWh)	9	0	9	100.0
Annual peak demand (GW)	1,062	908	154	14.5
Generation power capacity (GW)	2,532	2,198	334	13.2
Battery energy capacity (GWh)	4,362	3,809	553	12.7

A comparison between the results of PLEXOS and ReEDS indicates that these results are in agreement with differences explainable through the differences in the modeling scope between PLEXOS and ReEDS. Load results of PLEXOS show a 10.8% reduction in the annual load with GHP deployment in the Base and the Grid Decarbonization scenarios. In ReEDS, this reduction was 11.2%, showing similar reductions. The total reported load in terms of terawatt-hours is higher as reported by PLEXOS compared with that predicted by ReEDS because the PLEXOS results included the total energy used to charge battery storage.

Peak demand results of PLEXOS show a 12.9% reduction in the Base + GHP scenario and 14.5% reduction in the Grid Decarbonization + GHP scenario. The reported peak demand reduction in ReEDS is 17%. The small discrepancy between the results of PLEXOS and ReEDS is due to the differences in the reported metrics in the two models. In PLEXOS, the values reported in this section include storage charging and are a measurement of the national concurrent peak demand. In ReEDS, the peak demand is based upon the regional peak demands, which are not temporally concurrent, and does not consider battery charging. Further analysis indicates that the annual peak demand hour used in PLEXOS occurs during a summer daylight hour, which is a period with abundant solar production, incentivizing charging battery storage to meet the net peak demand period during a later time of the day. Therefore, the percentage of peak demand reduction in the PLEXOS results is lower than that predicted with ReEDS.

Another area of contrast with ReEDS is on the reported annual average wholesale electricity price and annual generator revenue (annual consumer payment for electricity). The wholesale electricity price reported by PLEXOS is equivalent to the weighted average of the locational marginal price (LMP) of electricity. LMP is an important price metric used in power markets in the United States and describes, at a specific location and time, the cost of producing the next unit of electricity. LMP is used by power markets to determine the settlement price for the energy sold by a power generator and is directly related to the generator's revenue. ReEDS has an equivalent metric for the energy component of the marginal system cost of electricity as described in Section 4.2.1.5. In the Base + GHP scenario, PLEXOS results showed a relatively larger cost reduction of 23% for LMP compared with a 7.5% reduction predicted by ReEDS. In the Grid Decarbonization + GHP scenario, PLEXOS results showed a reduction of 17% compared with 28% predicted by ReEDS. With the hourly temporal resolution, PLEXOS identified higher prices for energy in the Grid Decarbonization + GHP scenario ($112–$135/MWh) compared with ReEDS ($32–$42/MWh). It highlights a limitation of the available resolution in the ReEDS representation of power system operations.

4.2.2.2 Reliability Assessment Zone Peak Demand Results and Analysis

This section builds upon Section 4.2.1.3; a discussion of resource adequacy and its implementation within the ReEDS can be found there. This section focuses on the temporal granularity and operational detail available in the PLEXOS simulation, which gives more details regarding the operation of the electric power system in different scenarios.

Reliability assessment zones (RAZs) are aggregations of BAs used in ReEDS, within which the bulk power system is assessed to ensure resource adequacy. The RAZs are closely aligned with the regions used by NERC for regional assessments, which subdivide the interconnected power systems of North America based on the characteristics of the electric grid and the entities responsible for its operation. The area coverage of each RAZ is shown in Figure 2-4. In this subsection, the concurrent peak is calculated for each RAZ using PLEXOS. The calculation of the peak load includes the fixed hourly demand (from end uses) and grid demand for charging battery storage.

Figure 4-1 and Figure 4-13 show the PLEXOS results of peak load changes resulting from GHP deployment in each RAZ under the Base and the Grid Decarbonization scenarios in 2050 for the summer and winter, respectively. With Grid Decarbonization in nearly all regions, there is an increase in the peak load because of a higher reliance on battery storage in the electric power systems. Although peak load has historically been the benchmark for periods of the greatest stress to the electrical grid, it is different for systems with significant shares of wind and solar power. Summer afternoon peak demand coincides with high solar availability and be an opportune period for storage systems to charge using inexpensive electricity.

The increase in peak demand in the Grid Decarbonization scenario is indicative of this effect with peak demand increasing because of the charging of battery storage. The peak demand reduction resulting from GHP deployment increases in the Grid Decarbonization + GHP scenario because the hourly load reduced by GHP deployment reduces the reliance on battery storage for both summer and winter periods. This effect is observable in the Northeast Power Coordinating Council (NPCC), where peak demand reductions shown in PLEXOS results are achieved at a higher fraction for both summer and winter in the Grid Decarbonization + GHP scenario.

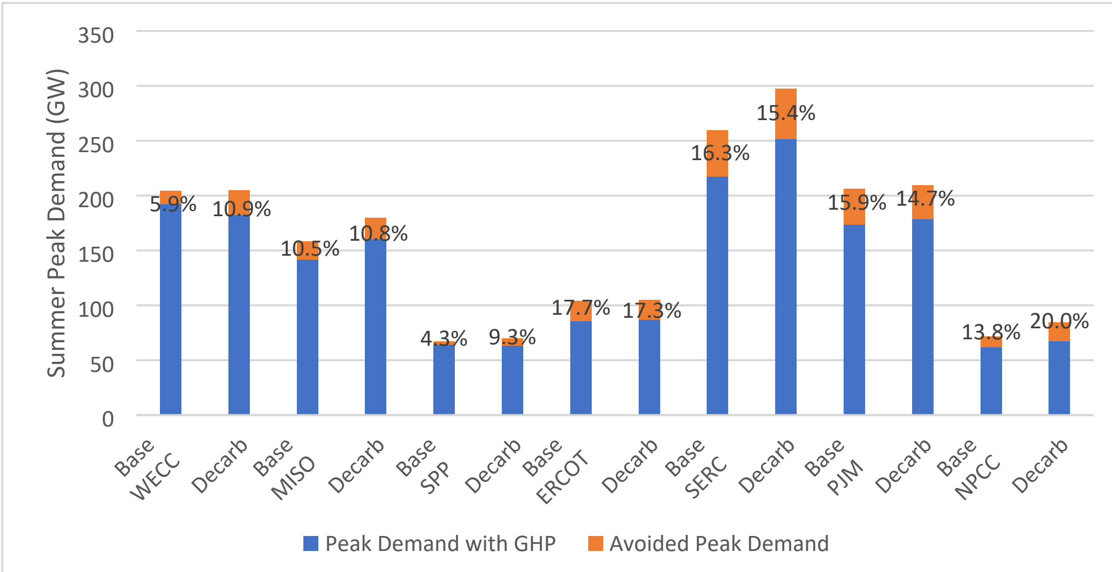


Figure 4-13. Summer peak demand in the Base and Grid Decarbonization scenarios; the blue bars are the peak demand by region, and orange bars are the avoided peak demand owing to demand reductions from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes. The percentage of avoided peak demand is shown in the figure's labels.

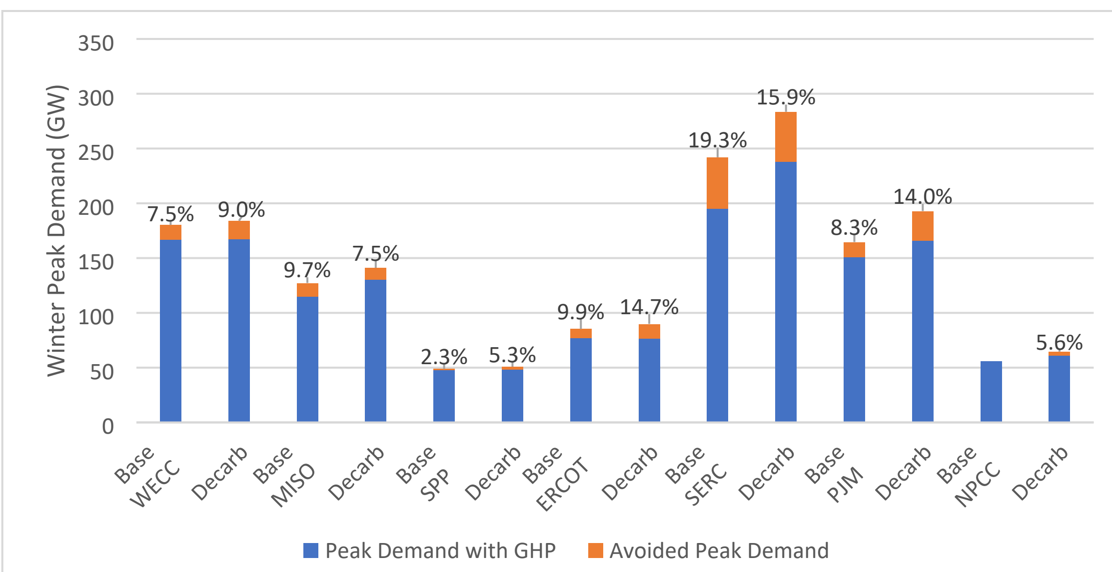
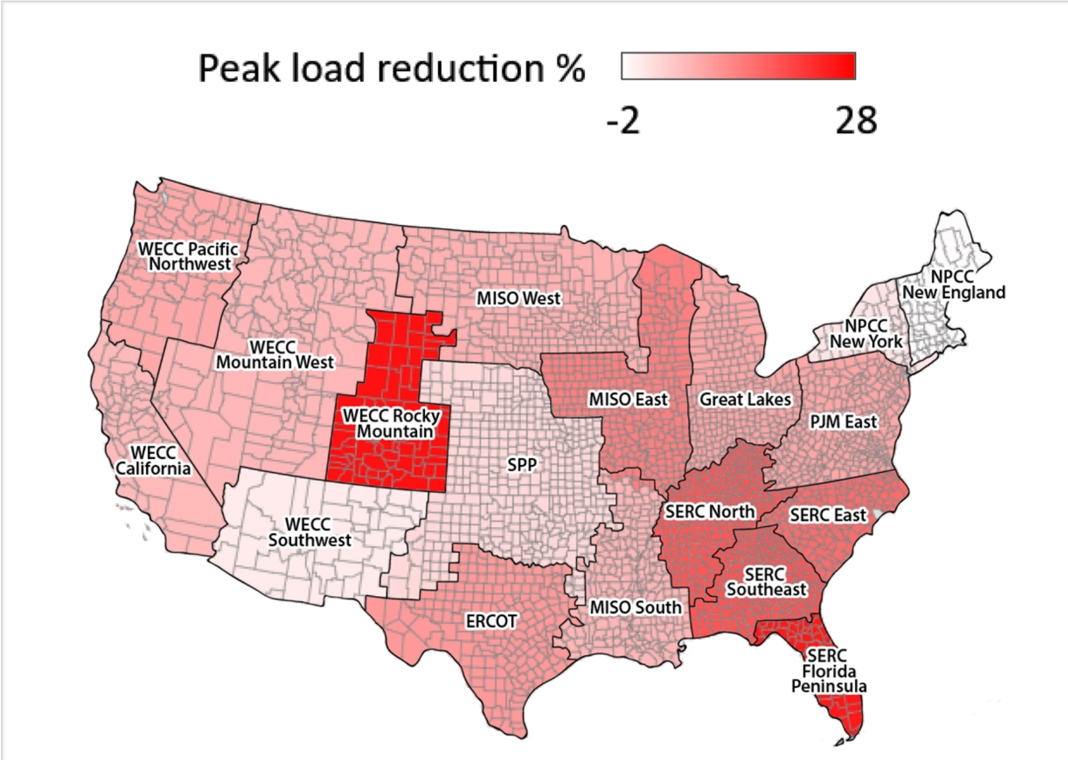


Figure 4-13. Winter peak demand in the Base and Grid Decarbonization scenarios; the blue bars are the peak demand by region, and orange bars are the avoided peak demand owing to demand reductions from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes. The percentage of avoided peak demand is shown in the figure's labels.

The seasonality results highlight the differences in effects derived from regional differences in climate and displaced HVAC technologies. Summer peak demand analysis shows reductions across all regions because of the higher cooling efficiency of the GHP system compared with existing conventional air-conditioning systems. This difference is particularly pronounced in the electric power systems managed by Electric Reliability Council of Texas (ERCOT) and SERC Reliability Corporation (SERC), which have a much higher peak demand reduction because these areas have a strong cooling demand in the summer.

In winter, the mass GHP deployment (including weatherization in SFHs) reduces peak demand most strongly in regions where heating is already electrified (e.g., using ASHPs). Here, SERC is most notable; having mild winters and a highly electrified heating system, the regional peak demand reduction ratio was 19%, and in the constituent RAZ, it was as high as 28%. In contrast, peak demand sees lower reductions in regions with high fossil fuel–dominated heating systems. In the region managed by NPCC, with harsher winters, a slight increase in electric consumption occurred in the Base + GHP scenario, with reduced battery charging in the Grid Decarbonization + GHP scenario yielding a reduction in peak demand. In these regions, the electricity consumed by a GHP for space heating is not offset by the avoided electricity for cooling, but there will be other operating costs, health, and decarbonization benefits from retrofitting fossil fuel heating systems in these regions with GHPs that fall outside of the PLEXOS analysis.

Figure 4- and Figure 4- show the percentages of avoided peak demand resulting from the mass GHP deployment for each RAZ for the summer and winter in the Base and Grid Decarbonization scenarios. In summer, the south, southeast, and east usually have a higher peak demand reduction after GHP deployment than other areas. These maps show the overlapping interactions between regional differences in climate and existing installed HVAC systems.



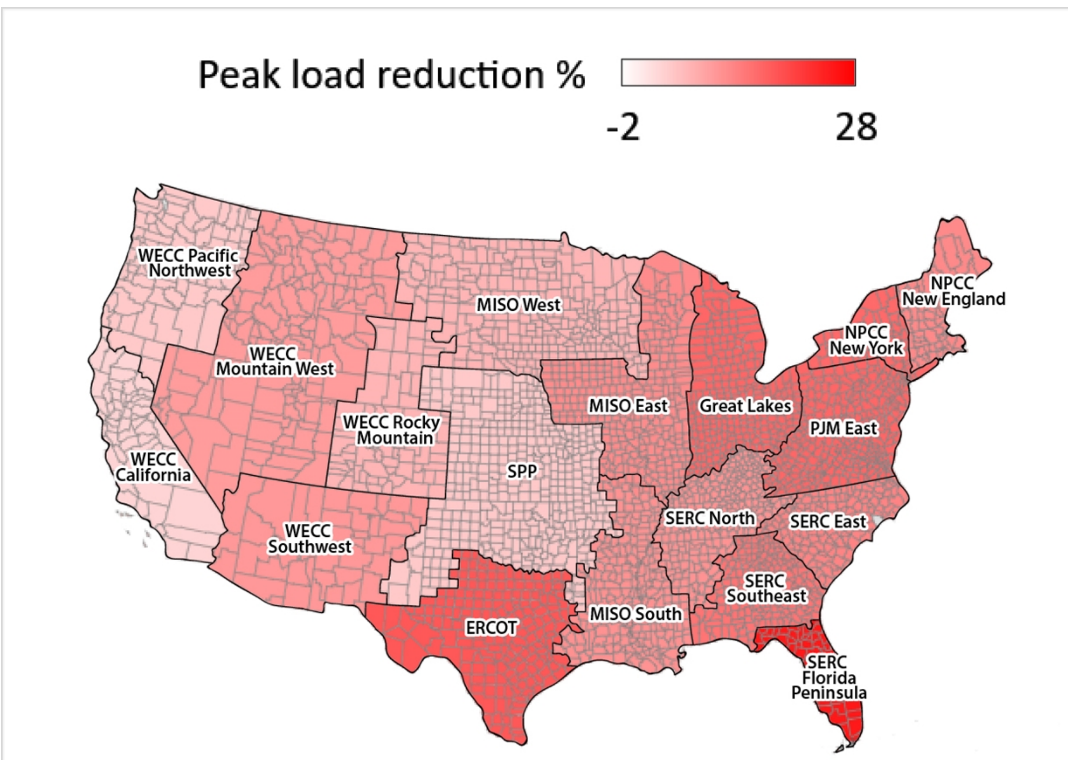


Figure 4-14. Peak electric demand reduction percentage in (top) winter and (bottom) summer at each RAZ resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Base scenario.

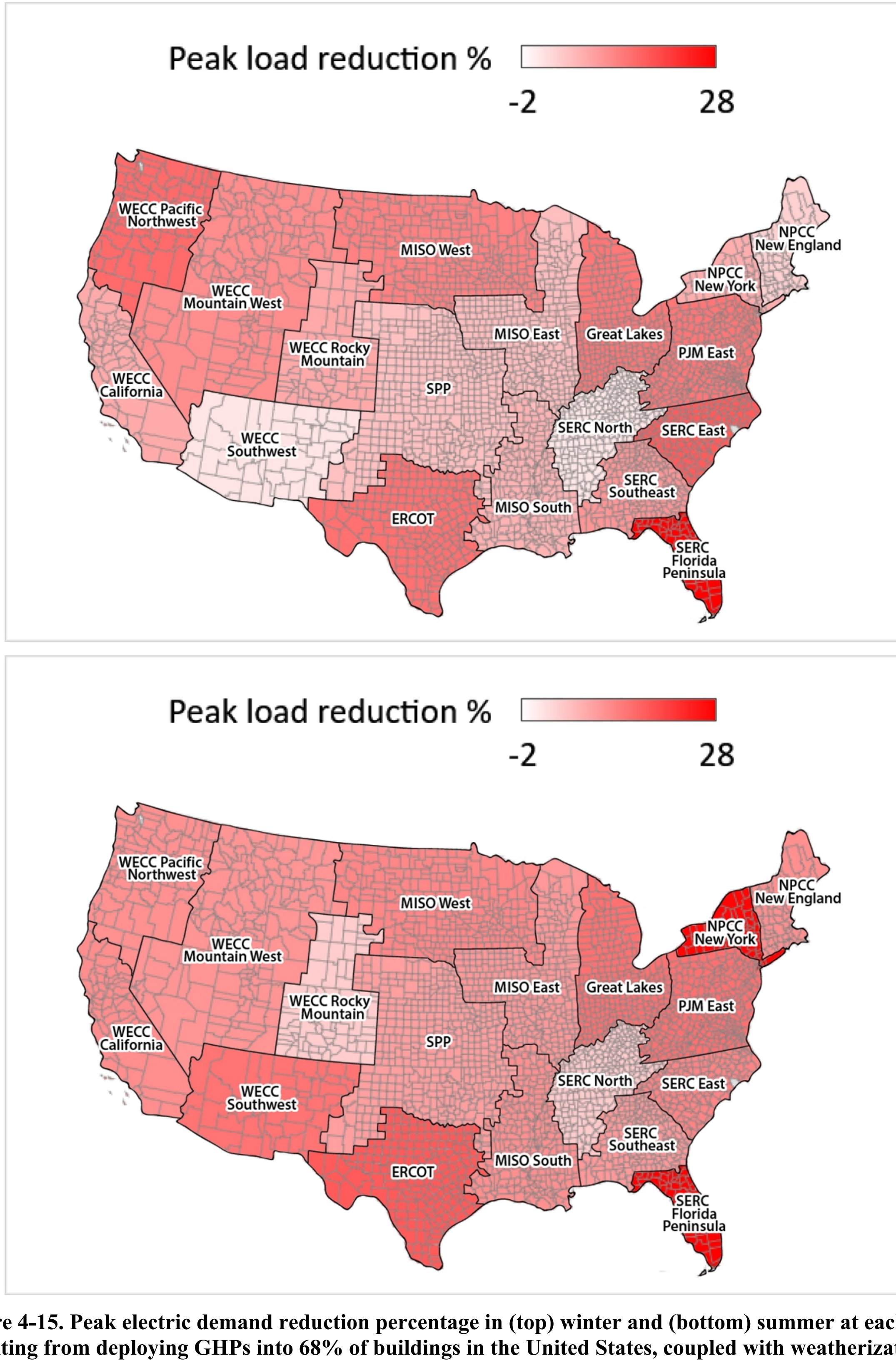


Figure 4-15. Peak electric demand reduction percentage in (top) winter and (bottom) summer at each RAZ resulting from deploying GHPs into 68% of buildings in the United States, coupled with weatherization in single-family homes, in the Grid Decarbonization scenario.

4.2.2.3 Regional (Balancing Area) Results and Analysis

To investigate the effect of GHP deployment at a finer spatial resolution, the peak demand at the BA level is examined in this subsection. Three BAs were selected based on their differences in climates and the currently used heating energy sources, including BA 1 in Western Washington, BA 94 in Georgia, and BA 134 in Maine. Table 4- and

Table 4- show the PLEXOS results of peak demand with and without the mass GHP deployment in the Base and Grid Decarbonization scenarios, respectively. Note that the timing of peak demand differs by BA because of the weather and differences in patterns of electric demand composition.

For BA 1 (Western Washington), the climate is relatively mild, so the energy consumption for heating and cooling is also moderate. It is a winter-peaking region. The GHP deployment (including weatherization in SFHs) can reduce the peak demand by 4.5% in summer in the Base scenario and achieve the same reduction in the Grid Decarbonization scenario. This BA is a highly electrified region, with only 50% of heating demand served by natural gas. GHP deployment in this BA reduces winter peak demand by 5.9% in both the Base and the Grid Decarbonization scenarios.

For BA 94 (Georgia), the summer is hot, and the winter is mild. Currently, grid demands are nearly balanced between summer and winter on the grid. Georgia also has a high degree of electrified heating within, with 60% of the building heating provided by natural gas and propane. GHP deployment reduces the summer peak by 14.1% because of the higher efficiency of the GHP in both the Base and Grid Decarbonization scenarios. In Georgia, the deployment of GHPs (including weatherization in SFHs) reduces the winter peak demand by a similar quantity as the summer peak reduction of 5 GW, or 15.3%, in the Base scenario and by 3 GW, or 9.2%, in the Grid Decarbonization scenario.

For BA 134 (Maine), the summer is warm, and the winter is very cold. Electricity makes up little of Maine's current heating demand in winter, which is mostly served by a mix of oil, propane, firewood, and natural gas. Thus, full electrification of building heating in this area increases electricity consumption. GHP deployment reduces the summer demand by 170 MW, or 7%, in both the Base and Grid Decarbonization scenarios. In contrast to other regions, there is an increase in the winter peak demand by 220 MW, or 8.3%, in the Base scenario and 140 MW, or 5.9%, in the Grid Decarbonization scenario.

Table 4-8. Regional analysis for the Base scenarios in 2050

Location	Season	Base (GW)	Base + GHP (GW)	Reduction (GW)	Reduction (%)
Western Washington	Summer (Aug. 17)	9.52	9.09	0.43	4.5
	Winter (Jan. 18)	12.62	11.87	0.75	5.9
Georgia	Summer (Jun. 30)	39.24	33.69	5.55	14.1
	Winter (Jan. 3)	33.1	28.05	5.05	15.3
Maine	Summer (Jul. 19)	2.40	2.23	0.17	7.1
	Winter (Jan. 20)	2.64	2.86	−0.22	−8.3

Table 4-9. Regional analysis for the Grid Decarbonization scenarios in 2050

Location	Season	Grid Decarbonization (GW)	Grid Decarbonization + GHP (GW)	Reduction (GW)	Reduction ratio (%)
Western Washington	Summer (Aug. 17)	9.52	9.09	0.43	4.5
	Winter (Jan. 18)	12.62	11.87	0.75	5.9
Georgia	Summer (Jun. 30)	39.24	33.69	5.55	14.1
	Winter (Jan. 3)	33.34	30.27	3.07	9.2
Maine	Summer (Jul. 19)	2.40	2.23	0.17	7.1
	Winter (Jan. 20)	2.36	2.50	−0.14	−5.9

4.3 DISCUSSION AND LIMITATIONS

The GHP impacts analysis is subject to the limitations affecting most forward-looking studies that are quantitative and qualitative. This study depends on fundamentally uncertain modeling input assumptions, including load shapes, growth, and future costs. ReEDS, PLEXOS, and the ReEDS-to-PLEXOS model translation have known limitations that were considered when analyzing results. For ReEDS-specific limitations and ReEDS-to-PLEXOS model translation limitations, see Ho et al. (2021). Both ReEDS and PLEXOS are techno-economic models and do not account for specific business structures, market power, or socioeconomic considerations. Qualitative results are limited by literature and an understanding of the conditions that would influence a future power system, which are limited by historical trends and the body of existing literature. These limitations are mitigated by collecting input from the diverse body of expertise among the authors and reviewers when drafting this report.

Changes in the electric load from GHP deployment assume linear deployment rates and no improvements in efficiency of the GHPs during the study period. Although the total deployment is aspirational, the rate of deployment and the fixed assumption around performance may be conservative. This study did not quantify the cost of GHP installation and the available land areas for installing GHP systems because the intention was to quantify the potential benefits to the grid from the GHP deployment. Future analyses accounting for the costs and efficiency improvement of GHPs, as well as constraints of available land areas, could better explore the GHP deployment rates in various markets.

Although land use is an important consideration for questions of equity and environmental impact, this study did not quantify the relative changes in land use among technologies. Reductions in solar and wind installation from the mass GHP deployment will see reductions in long-term land use. GHP deployment for commercial and residential buildings is known to have minimal long-term land use impacts.

4.4 SUMMARY

In this section, the electric power sector analysis based on ReEDS and PLEXOS simulations revealed various impacts on the electric sector from deploying GHP systems in all applicable buildings (including weatherization in SFHs). First, the mass deployment of GHPs can reduce the generation and capacity needs of the electric power system by up to 11% and 13.2%, respectively, in 2050. The peak demand in some zones can be reduced up to 28%, which will ease grid operations and defer the installation of new generation capacities. Second, the mass GHP deployment reduces the reliance on carbon-emitting power generation in the Base scenario and cuts the transmission expansion need by approximately one-third in the Grid Decarbonization scenario. Third, the deployment of GHPs can help reduce the requirements for summer and winter resource adequacy. In the Base scenario, it reduces the natural gas generation capacity requirements in the summer, whereas in the Grid Decarbonization scenario, all natural gas power plants are retired, so the summer RA eligible capacity reduction is mainly a reflection of reduced capacity requirements from H_2-CTs. In winter, the RA eligible capacity in 2050 with the GHP deployment is less than the 2022 reference, and such a reduction is even more significant in the Grid Decarbonization scenario. It can also reduce the wholesale, system-level electricity price because of the decreased peak demand, the annualized cost savings from reduced fuel use in power plants, and the relaxed reserve requirements. Importantly, these system cost reductions represent savings that could be available as incentives to reduce the cost to consumers for retrofitting buildings with GHPs.

5. PRELIMINARY REGIONAL GRID RELIABILITY ANALYSIS

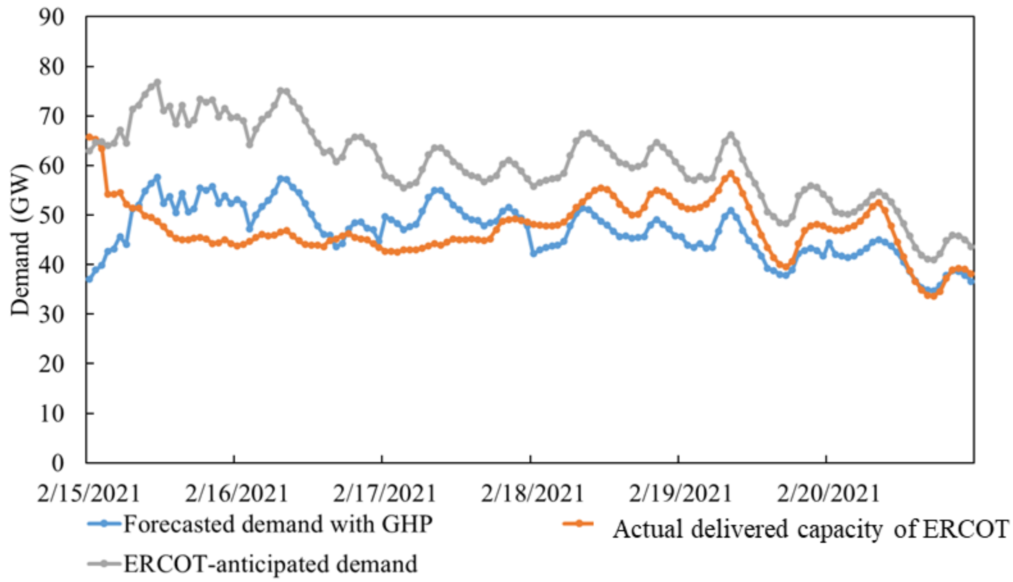
This section presents preliminary simulation results aimed at analyzing the effects of GHP deployment on grid reliability. Instead of conducting a comprehensive nationwide analysis, the focus is narrowed to assess regional grid reliability. Specifically, this section examines a blackout event that occurred during a winter storm in Texas, which commenced on February 15, 2021, and persisted for multiple days. During this severe winter storm, the electricity demand of the ERCOT power grid surged to a peak of 69 GW, surpassing the previous winter record of 66 GW. As a result, more than 4.5 million households (approximately 10 million Texans) were left without electricity at the height of this event. The associated economic losses attributable to this calamity were estimated at $130 billion (Busby et al. 2021).

The blackout event was caused by the frigid conditions brought about by the winter storm. The extreme cold weather led to a sharp decline in gas supply because of various factors such as freezing occurring at natural gas wells and gathering lines, power outages at compressor stations, and other related issues. Furthermore, the demand for gas surged significantly because approximately 40% of households in Texas rely on gas and propane for space heating during cold weather conditions. Consequently, the combination of decreased gas supply and increased consumption resulted in a shortage of approximately 30 GW in generation capacity. However, the electricity demand increased further regardless of the generation capacity shortage because approximately 60% of Texas households employ electricity for space heating. In this case, the deficiencies in the gas system, combined with insufficient generation capacity, led to significant disparity between supply and demand, which created a precarious imbalance that ultimately culminated in the occurrence of the blackout event (Busby et al. 2021).

As illustrated in the preceding sections, GHP retrofitting presents an opportunity to eliminate gas consumption and reduce the electricity demand of buildings. Given these premises, the widespread deployment of GHPs in Texas could offer a means to mitigate blackout events. To evaluate the potential effectiveness of GHP retrofitting in mitigating the 2021 winter storm blackout, a specific scenario was considered. This scenario assumes that all applicable buildings within the ERCOT had already undergone GHP retrofitting before the onset of the storm. To quantify the effects, the resulting electric demand attributable to GHP retrofitting was calculated. This value was then compared with the anticipated electric demand in the absence of GHP retrofitting, which was obtained from the EIA (EIA 2021). The historical demand (i.e., the actual delivered electric power) that was experienced in this event was limited by the capacity of the power plant. Appendix E provides more details of the calculation of the electric demand resulting from GHP retrofitting.

5.1 ANALYSIS RESULTS

Figure 5-1 presents a comparison between the anticipated electricity demand of the ERCOT and the calculated electricity demand resulting from the implementation of mass GHP retrofitting. The anticipated electricity demand was the one forecasted by the ERCOT for 2021. The calculated electricity demand with GHP retrofitting was obtained by first calculating the demand reduction owing to GHP retrofitting and then subtracting it from the anticipated electricity demand. As shown in Figure 5-1, the anticipated electricity demand exhibited a sharp increase during the 2021 winter storm. Conversely, the electricity demand was calculated to be reduced through GHP retrofitting, and the reduction is pronounced during the summer and winter. This comparison demonstrates that if all applicable buildings within the ERCOT had undergone GHP retrofitting, the anticipated electricity demand would have been significantly reduced, which would be vital in mitigating the strain on the grid such as what occurred during the 2021



winter storm.

Figure 5-2. shows three profiles of electricity demand more granularly during the 2021 winter storm. Along with the anticipated and calculated electricity demand, the delivered capacity of ERCOT recorded during the 2021 winter storm is also shown. As shown in Figure 5-2, the delivered capacity was less than the anticipated demand during the winter storm, which implies that there was a power outage. The significance of a system blackout can be measured by the difference between the delivered capacity and the anticipated electricity demand. If mass GHP retrofits were achieved in Texas before the 2021 winter storm, the newly anticipated electricity demand would become the calculated electricity demand, which is significantly smaller than the anticipated demand. Although the calculated electricity demand with GHP retrofitting is still higher than the delivered capacity for certain periods, the severity and duration of the power outage would be much smaller than that before GHP retrofitting.

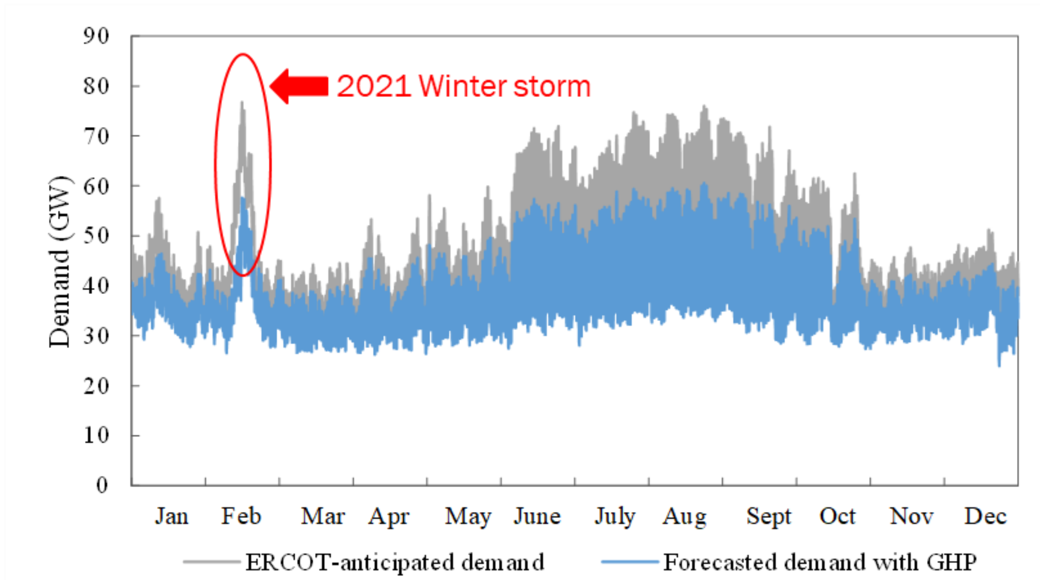


Figure 5-1. Hourly electricity demand profile of ERCOT before and after GHP retrofit in 2021.

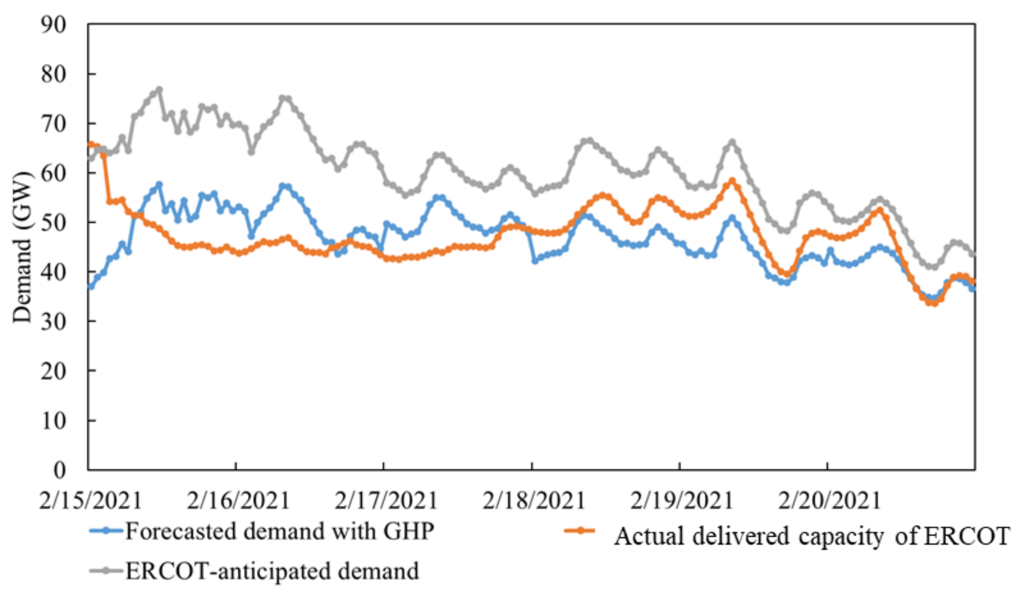


Figure 5-2. Hourly demand profiles of six consecutive days during the 2021 winter storm in Texas.

Table 5-1 provides a comprehensive overview of the most severe outage periods during the 2021 winter storm. It reveals that during these critical periods, 36.5% to 39.5% of the anticipated electricity demand was left unmet. However, when considering GHP retrofitting, the unserved electricity demand ratio would have been notably reduced, ranging from 15.4% to 20.6%. These findings strongly indicate that widespread deployment of GHPs can significantly enhance the reliability of the power system.

Table 5-1. Electricity demand during the most severe outage periods in the 2021 Texas winter storm

Time	Without GHP retrofitting	With GHP retrofitting

	Unserved demand (GW)	Served demand (GW)	Outage ratio (%)	Unserved demand (GW)	Served demand (GW)	Outage ratio (%)
2/15/2021, 11 a.m.	28.04	48.75	36.5	8.88	48.75	15.4
2/15/2021, 3 p.m.	27.10	44.96	37.6	9.43	44.96	17.3
2/15/2021, 6 p.m.	27.86	45.45	38.0	10.00	45.45	18.0
2/15/2021, 7 p.m.	27.67	45.11	38.0	9.95	45.11	18.1
2/15/2021, 8 p.m.	28.89	44.26	39.5	11.49	44.26	20.6
2/16/2021, 7 a.m.	28.51	46.56	38.0	10.82	46.56	18.9
2/16/2021, 8 a.m.	28.15	46.85	37.5	10.36	46.85	18.1
2/16/2021, 9 a.m.	27.12	45.81	37.2	9.72	45.81	17.5

Notably, the analyses presented thus far primarily focus on the reduction of electricity demand, which represents just one of the benefits achievable by GHP retrofitting. Another notable advantage is the concurrent decrease in gas consumption for heating within buildings. The saved gas can be redirected toward electricity power generation, thereby augmenting the overall power supply. Considering the interdependence of gas and electricity systems, an adequate electricity supply can enable gas supply, leading to mutual improvement and reinforcing system stability. Thus, the widespread implementation of GHPs could have potentially prevented the large-scale blackout in Texas during the 2021 winter storm.

5.2 SUMMARY

The preliminary analysis conducted demonstrates that mass GHP retrofitting can effectively enhance the operational reliability of the power grid in Texas, particularly during extreme weather conditions. This improvement stems from the substantial reduction in electricity demand achieved through GHP retrofitting, thereby reducing the strain on the power system.

Considering the ongoing effects of climate change, Texas and other areas will likely encounter a greater frequency and intensity of extreme weather events in the coming years. Notably, events such as the polar vortex experienced in December 2022 are expected to exert significant pressure on the electricity infrastructure. These circumstances are especially challenging for areas reliant on ASHPs and electric heaters for building heating and cooling. Under such circumstances, there is an increased risk of rolling blackouts or uncontrolled blackouts that affect many consumers and result in substantial economic losses. Therefore, more efficient heating and cooling systems such as GHPs must be adopted to alleviate the electricity demand burden, thereby improving the resilience and robustness of the electric power system.

6. CONCLUSIONS AND FUTURE WORK

This study began with a large-scale building stock energy simulation to assess the effects of mass GHP deployment, which is combined with weatherization of SFHs (i.e., reducing air infiltration and ductwork leakage), on electricity usage and on-site carbon emissions in the building sector. The simulation results show that retrofitting 68% of all existing building floor space in the United States (78% of residential floor space and 43% of commercial floor space of the 2018 building stock[23]) with GHP systems, along with measures for reducing OA infiltration and ductwork leakage in SFHs, can save 401 TWh of

[23] In this analysis, GHP retrofits excluded 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.

electricity and eliminate 5,138 billion MJ of fossil fuel consumption (e.g., natural gas, heating oil, propane) (approximately 4,747 billion ft^3 of natural gas equivalent) each year compared with the electricity and fuel consumption of the existing building stock in 2018. The reduced on-site fossil fuel consumption at buildings would avoid carbon emissions equivalent to 342 MMT CO_2 each year. If GHP deployment increases linearly from 2020 until reaching its maximum potential by 2050, fuel costs of US$(2021)1,020 billion would be saved, and 5,290 MMT CO_2e emissions would be avoided over 30 years by replacing the on-site consumptions of fossil fuels with GHPs for space heating.

Retrofitting existing HVAC systems with GHP systems has different effects in different regions. Large reductions in annual electricity consumption occur in the southern United States because of the dominance of air-conditioning in total annual energy use. In the northern United States, GHP retrofits result in high on-site carbon emission reductions because of the dominance of existing combustion-based heating systems (i.e., furnaces or boilers using gas, propane, and fuel oil). In many regions, the gain in efficiency during the cooling season more than offsets the increase in electrified heating load, resulting in a full building electrification with reductions in total annual electricity use. It is noteworthy that roughly 50% of the benefits described in this report (carbon, energy, and system cost reductions) are attributable to the superior efficiencies of GHPs with the remaining benefits attributable to reducing OA infiltration and ductwork leakage in SFHs. Thus, the key to realizing the enormous value proposition is through a combination of both deep efficiency measures, which should be considered for all future retrofits.

The US electric power system were analyzed in several scenarios, including Base, Grid Decarbonization, and economy-wide decarbonization (i.e., the EFS scenario). This analysis revealed various effects on the electric power system resulting from the mass deployment of GHPs (including weatherization in SFHs). The following effects can be expected if the maximum deployment of GHPs is realized by 2050:

- Reduce the requirement for annual electricity generation in the contiguous United States[24] by 585 TWh, 593 TWh, and 937 TWh compared with the Base, Grid Decarbonization, and EFS scenarios, respectively.
- Reduce the needed generation and storage capacity by 173 GW, 345 GW, and 410 GW compared with the Base, Grid Decarbonization, and EFS scenarios, respectively.
- Avoid transmission additions by 3.3 TW·mi (a 17.4% reduction), 36.7 TW·mi (a 33.4% reduction), and 65.3 TW·mi (a 37.6%) compared with the Base, Grid Decarbonization, and EFS scenarios, respectively.
- Reduce the required capacity for resource adequacy, mostly from power plants using fossil fuels, by 102 GW in summer and 95 GW in winter compared with the Base scenario. In the Grid Decarbonization scenario, 103 GW (summer) and 101 GW (winter) of capacity would no longer be needed. In the EFS scenario, substitution of ASHPs with the mass GHP deployment reduces the resource adequacy requirement by 127 GW in summer and 185 GW in winter.
- Eliminate 217 MMT CO_2 emissions each year from the US electric power system by 2050 compared with the Base scenario. However, in the Grid Decarbonization scenario, GHP deployment does not affect carbon emissions from the electric power system because the carbon emission constraint of the electric power system is determined by the predefined grid decarbonization target. GHP deployment could also avoid CO_2 emissions related to end-use heating in the building sector. The deployment of GHPs leads to a 7,351 MMT cumulative CO_2 emissions reduction from 2022 to 2050 in the Base + GHP scenario. In the Grid Decarbonization + GHP scenario, the deployment of GHPs primarily

[24] This excludes Alaska, Hawaii, and US territories because of limited data for conducting a detailed analysis.

reduces carbon emissions in the building sector (4,318 MMT from 2022 to 2050). Compared with the EFS scenario, the mass deployment of GHPs reduces 2,178 MMT cumulative CO_2 emissions from 2022 to 2050.

- Reduce the wholesale cost for electricity. The mass GHP deployment reduces peak electricity demand and flattens annual electricity use. As a result, the wholesale cost for electricity in 2050 can be lowered by 6% in the Base + GHP scenario, 12% in the Grid Decarbonization + GHP scenario, and 8% in the EFS + GHP scenario. From 2022 to 2050, the reduced wholesale cost decreases electricity payments from consumers by $316 billion in the Base + GHP scenario, $557 billion in the Grid Decarbonization + GHP scenario, and $606 billion in the EFS + GHP scenario (all present values considering a 5% discount rate).

- Reduce the cumulative system cost of electricity (including the capital costs of generators and transmission systems, as well as the costs for operating the generators and the grid) by $145 billion (a 5.1% reduction) in the Base + GHP scenario, by $241 billion (a 7.2% reduction) in the Grid Decarbonization + GHP scenario, and by $306 billion (a 7.4% reduction) in the EFS + GHP scenario.

- Reduce the peak load in all RAZs in the summer by 3% to 28%. In the winter, GHPs can also reduce the peak load for most areas; in the Southeast, where electric heating (e.g., ASHPs with supplemental electric resistance heaters) is widely used, the peak load reduction ratio can be up to 28%. Notably, the peak load is less reduced in areas where fossil fuel–based heating is used. A case study indicates that mass deployment of GHPs could improve the operational reliability of Texas electric power system in extreme winter weather events. It thus will reduce rolling blackouts, which could affect many consumers and result in high economic losses.

To address the limitations of the current study and generate more useful information to utility companies and decision-makers, the following actions are recommended:

- Conduct a regional analysis, such as for the service territory of a particular electric grid system or for a specific group of buildings in each county, to investigate the effects and costs of implementing GHPs. This analysis should include (1) CO_2 and energy cost reduction from eliminating natural gas combustion; (2) jobs to retrofit buildings and drill boreholes for implementing GHPs in applicable buildings; (3) water consumption in the electric power system resulting from mass GHP deployment, as well as water use in the cooling towers of commercial buildings; and (4) changes in grid assets (e.g., avoided lithium batteries), infrastructure development, and cost of transmission.

- Expand the building sector analysis to account for improvement in building energy efficiency, including improvement in building envelopes, the energy efficiency of conventional HVAC systems and GHP systems, and outdoor air ventilation controls.

- Develop a web-based interactive national map with built-in analytical tools to present the results of the impact analysis, including building and grid simulation results. The map will support data-driven research that explores the environmental and socioeconomic benefits associated with GHP deployment.

- Investigate the cost reduction potential resulting from the mass manufacturing of GHP units and the scale of economy for GHE installation.

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APPENDIX A. CHARACTERISTICS OF THE PROTOTYPE BUILDING MODELS USED IN THIS STUDY AND THE REPRESENTATIVE CITIES OF THE 14 US CLIMATE ZONES

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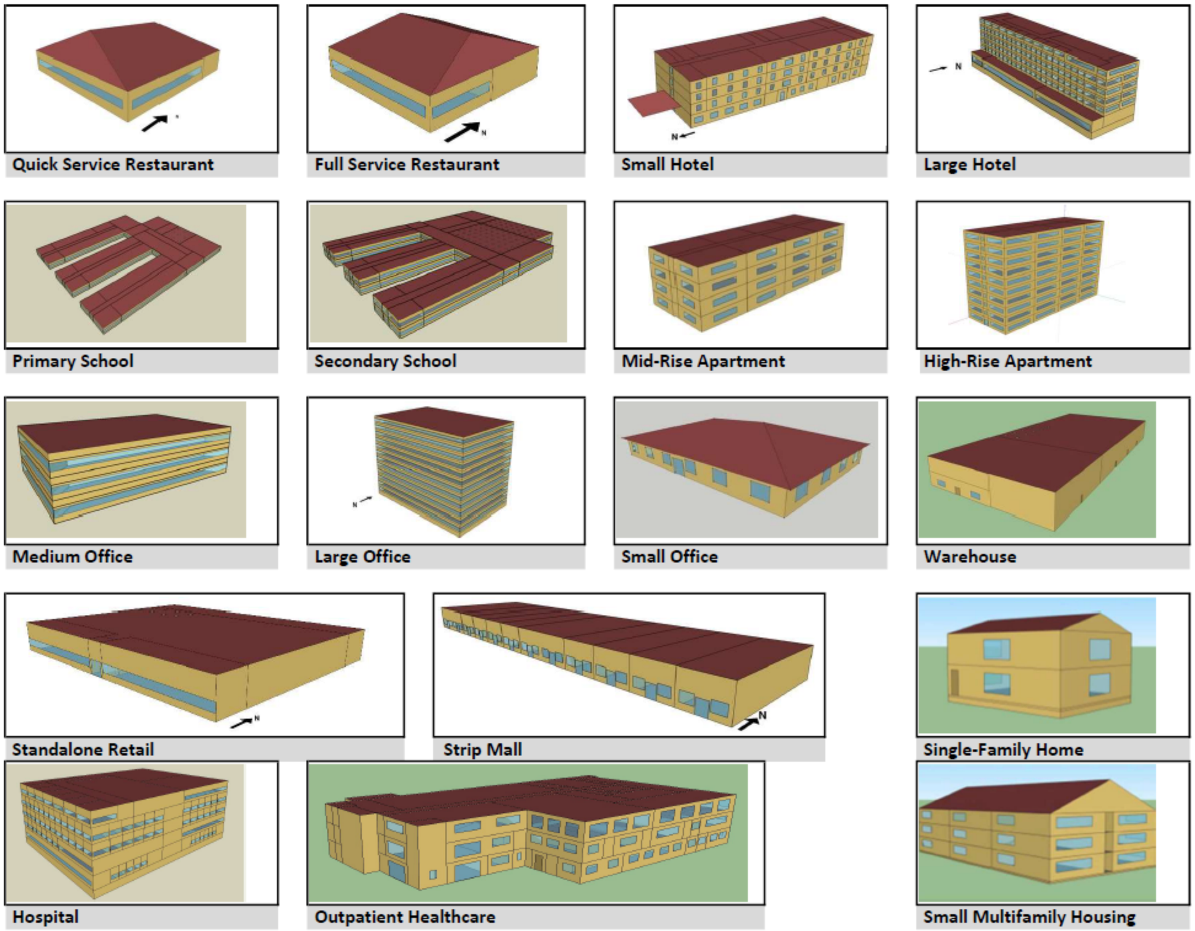

Figure A-1. 3D renderings of the commercial and residential prototype building models used in this study.

Table A-1. Total floor area and existing HVAC equipment of commercial and residential prototype buildings used in this study (designed following the 2007 edition of ANSI/ASHRAE/IES Standard 90.1 for commercial buildings and the 2006 edition of IECC for residential buildings)

Building description	Total floor area (ft^2)	Heating equipment	Cooling equipment
Small office	5,500	Heat pump with a backup gas furnace: 7.7 Heating Seasonal Performance Factor	Heat pump: seasonal energy efficiency ratio (SEER) 13
Medium office	53,600	Gas furnace: 80% burner efficiency	Packaged terminal air-conditioner (PTAC): energy efficiency ratio (EER) 9.3
Large office	498,600	Gas boiler: 80% thermal efficiency; water source heat pump: Heating COP 4.2	Water-cooled centrifugal chillers: 6.2 COP; water-source direct expansion (DX) cooling coil for data center and IT closets: EER 12

Table A-1. Total floor area and existing HVAC equipment of commercial and residential prototype buildings used in this study (designed following the 2007 edition of ANSI/ASHRAE/IES Standard 90.1 for commercial buildings and the 2006 edition of IECC for residential buildings) (continued)

Building description	Total floor area (ft^2)	Heating equipment	Cooling equipment
Standalone retail	24,695	Gas furnace: 80% burner efficiency; standalone gas furnace for entrance: 80% burner efficiency	PTAC: EER 9.3–10.1; no cooling for entrance
Strip mall	22,500	Gas furnace: 80% burner efficiency	PTAC: EER 9.5–10.1; no cooling for entrance
Primary school	73,960	Gas furnace: 80% thermal efficiency; gas boiler: 80% thermal efficiency	PTAC: EER 9.3–10.1
Secondary school	210,900	Gas furnace: 80% thermal efficiency; gas boiler: 80% thermal efficiency	PTAC: EER 9.3; air-cooled chiller: 2.7 COP (1.3 kW/ton)
Outpatient healthcare	40,950	Gas boiler: 80% thermal efficiency	DX cooling: EER 9.3
Hospital	241,410	Gas boiler: 80% thermal efficiency	Water cooled chillers: 6.1 COP (0.6 kW/ton)
Small hotel	43,200	PTAC with electric resistance, gas furnace: 80% burner efficiency; electric cabinet heaters for storage and stairs	PTAC: EER 9.3–11; split system with DX cooling: SEER 13; no cooling for storage and stairs
Large hotel	122,132	Gas boiler: 80% thermal efficiency	Air-cooled chiller: 2.7 COP (1.3 kW/ton)
Warehouse	49,495	Gas furnace: 80% burner efficiency	PTAC: 9.5 EER; SEER 13
Quick service restaurant	2,500	Gas furnace: 80% burner efficiency	PTAC: EER 9.5–10.1
Full service restaurant	5,502	Gas furnace: 80% burner efficiency	PTAC: EER 9.3–10.1
Mid-rise apartment	33,700	Gas furnace: 80% burner efficiency	Split system DX: SEER 13
High-rise apartment	84,360	Water source heat pumps: Heating COP 4.2	Water source heat pumps: EER 11.2–12.0
Single-family home (SFH)	2,376	Gas furnace	Central air conditioner: SEER 13
SFH	2,376	Oil furnace	Split system DX: SEER 13
SFH	2,376	Heat pump	Split system DX: SEER 13
SFH	2,376	Electric resistance	Split system DX: SEER 13
Small multifamily housing	21,600	Gas furnace	Split system DX: SEER 13
Small multifamily housing	21,600	Oil furnace	Split system DX: SEER 13
Small multifamily housing	21,600	Heat pump	Split system DX: SEER 13
Small multifamily housing	21,600	Electric resistance	Split system DX: SEER 13

Table A-2. The 14 US climate zones included in this study, along with representative cities

Climate zone	Representative city
1A	Miami, Florida
2A	Houston, Texas
2B	Phoenix, Arizona
3A	Atlanta, Georgia
3B	Las Vegas, Nevada
3C	San Francisco, California
4A	Baltimore, Maryland
4B	Albuquerque, New Mexico
4C	Seattle, Washington
5A	Chicago, Illinois
5B	Boulder, Colorado
6A	Minneapolis–St. Paul, Minneapolis
6B	Helena, Montana
7A	Duluth, Minneapolis

APPENDIX B. PERFORMANCE CURVES AND FAN EFFICIENCIES OF GEOTHERMAL HEAT PUMPS

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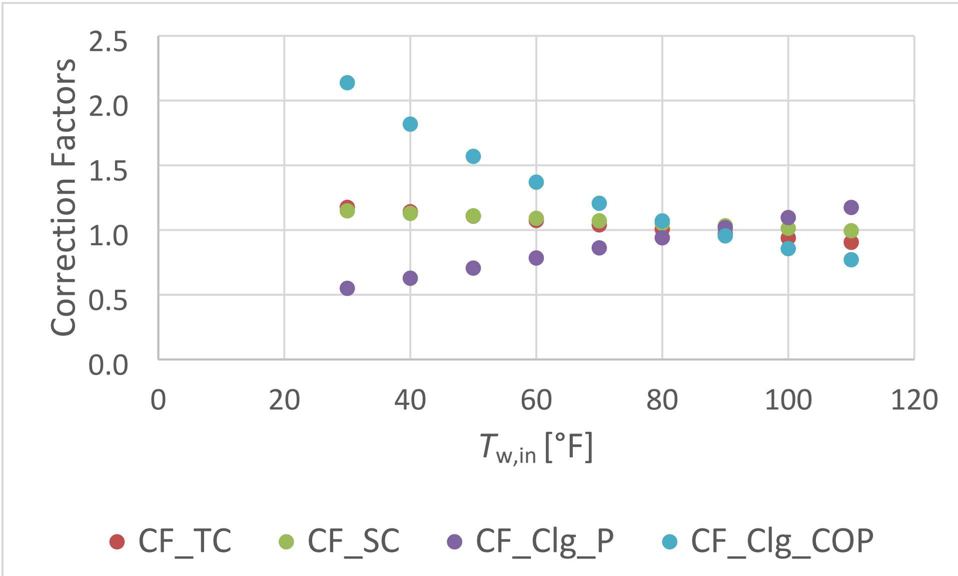


$T_{w,in}$: The temperature of water entering the source side of the geothermal heat pump (GHP)

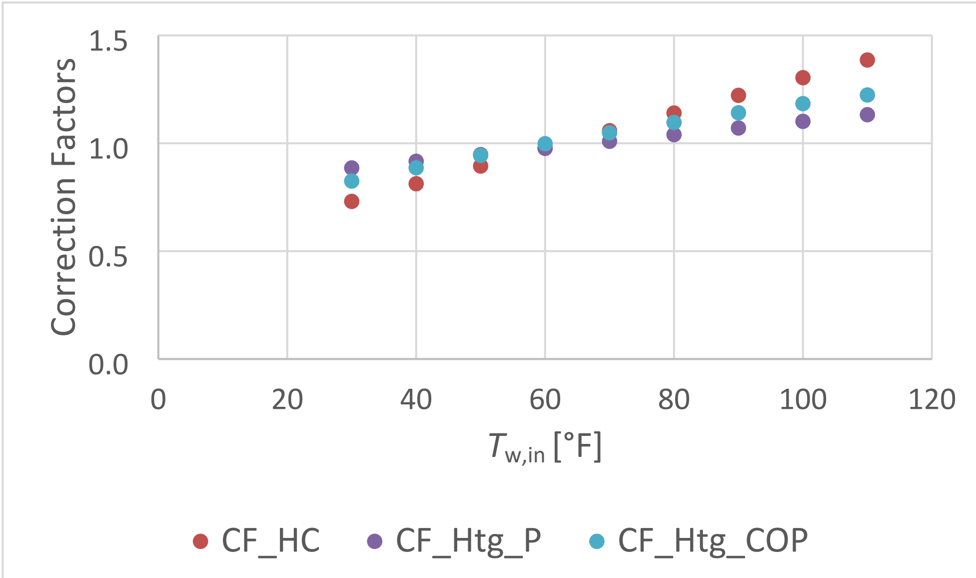
CF_TC: Correction factor for total cooling capacity, which is the ratio of the actual total cooling capacity to the nominal total cooling capacity at the rating condition

CF_SC: Correction factor for sensible cooling capacity, which is the ratio of the actual sensible cooling capacity to the nominal sensible cooling capacity at the rating condition

CF_Clg_P: Correction factor for cooling power consumption, which is the ratio of the actual power consumption to the nominal power consumption at the rating condition in cooling mode

CF_Clg_COP: Correction factor for cooling coefficient of performance (COP), which is the ratio of the actual COP to the nominal COP at the rating condition in cooling mode

Figure B-1. Performance curves of the GHPs in cooling mode.



$T_{w,in}$**:** The temperature of water entering the source side of the GHP

CF_HC: Correction factor for heating capacity, which is the ratio of the actual heating capacity to the nominal heating capacity at the rating condition

CF_Htg_P: Correction factor for heating power consumption, which is the ratio of the actual power consumption to the nominal power consumption at the rating condition in heating mode

CF_Htg_COP: Correction factor for heating COP, which is the ratio of the actual COP to the nominal COP at the rating condition in heating mode

Figure B-2. Performance curves of the GHPs in heating mode.

Table B-1. Efficiency and pressure rise of fans used in the modeled GHPs and the fans used in the existing HVAC systems of the prototype single-family homes

Variable	GHP fan	Existing fan
Motor efficiency	0.9	0.65
Fan total efficiency	0.7	0.38
Pressure rise (pa)	75	400

APPENDIX C. IMPACT ANALYSIS OF OUTDOOR AIR INFILTRATION ON HEATING AND COOLING LOADS OF SINGLE-FAMILY HOMES

APPENDIX C. IMPACT ANALYSIS OF OUTDOOR AIR INFILTRATION AND DUCTWORK LEAKAGE ON HEATING AND COOLING LOADS OF SINGLE-FAMILY HOMES

Outdoor air (OA) infiltration and ductwork leakage of an HVAC system significantly affects the heating and cooling demands of buildings, especially for single-family homes (SFHs). Depending on the climate and air tightness of a building envelope (e.g., exterior walls, ceilings, roofs, windows, and doors), the OA infiltration rates vary significantly from building to building. For SFHs in the United States, the majority of HVAC ductwork is installed in unconditioned attic space, where the air temperature is close to that of the outdoor ambient. Thus, air leakage and the associated energy loss from the ductwork could significantly increase the energy consumption for keeping the room temperature at desired set points.

To quantify the effects of OA infiltration and ductwork leakage on the heating and cooling energy consumption of SFHs, simulations were performed with the US Department of Energy's prototype SFH models across 16 climate zones (CZs) in the United States (Figure C-1). The prototype SFH models developed following the 2006 edition of the International Energy Conservation Code (IECC) were selected to represent existing SFHs. The 2006 edition of the IECC does not specify the minimum allowed OA infiltration rate and ductwork leakage. An airflow network was used in the prototype model to simulate the OA infiltration and ductwork leakage.[42] Four SFH models are in each CZ, and each has a different heating system, including an electric resistance heater, air-source heat pump, oil furnace, and gas furnace. The first set of 64 cases model OA infiltration and ductwork leakage using the airflow network implemented in the original prototype models. The second set of 64 cases eliminate OA infiltration and ductwork leakage by removing the airflow network.

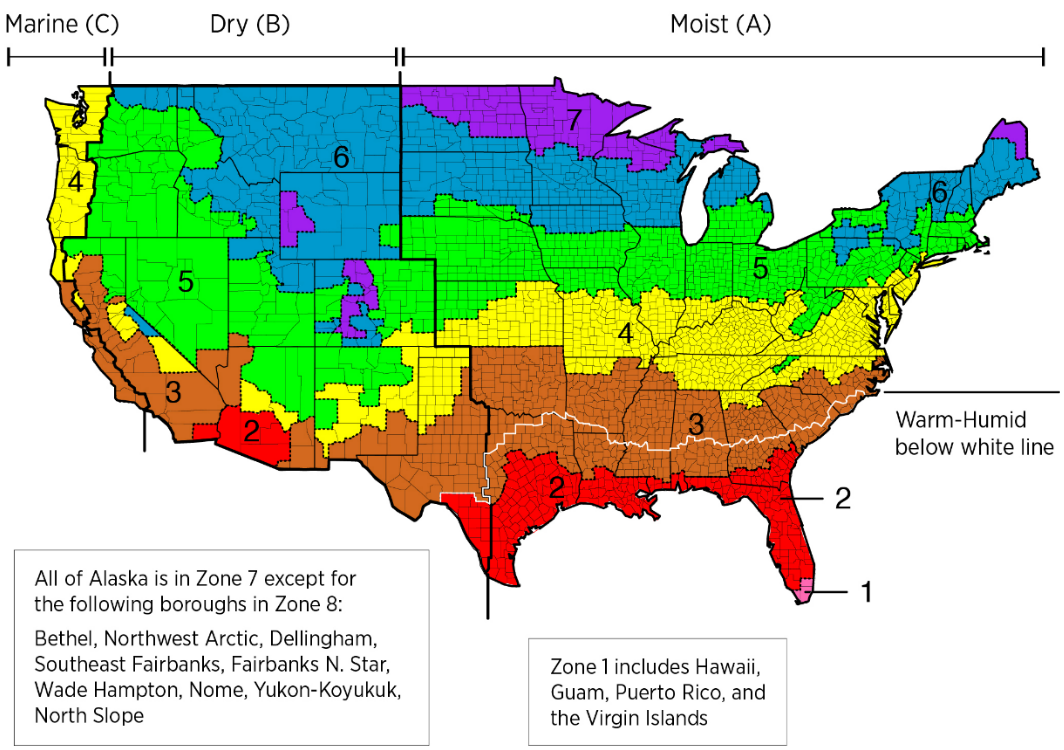


Figure C-1. CZ map for the United States. (Source: 2012 IECC, accessible at https://codes.iccsafe.org/content/IECC2012.)

[42] https://www.energycodes.gov/prototype-building-models

Figure C-2 shows the simulation results of the contribution of OA infiltration and ductwork leakage to the annual heating and cooling energy of the prototype SFHs at each CZ. The OA infiltration and ductwork leakage contribute 48% to 77% of the annual energy consumption for space heating. The contribution is higher in colder CZs because of the larger temperature difference between the ambient and the indoor air. For the annual space cooling energy consumption, the contribution ranges from −39% to 27%. The negative contributions are only for the three CZs (3C, 4C, and 5C) with marine weather, where the ambient temperature is mild and OA infiltration can cool the SFHs, thus reducing the cooling energy consumption. In terms of the annual heating and cooling energy consumption, the contribution of OA infiltration and ductwork leakage is between 21% and 71% for SFHs built following the 2006 edition of the IECC.

This analysis clearly indicates that OA infiltration and ductwork leakage contribute significantly to the annual heating and cooling energy consumption of SFHs, especially in cold climates. OA infiltration and ductwork leakage can be reduced by sealing the gaps, holes, and cracks in the ceilings, exterior walls, and ductwork, as well as applying weather strips to windows and doors.[43] According to previous studies, air sealing can reduce heating energy consumption by 30%–50% (Chan 2013, Hassouneh et al. 2012, Jokisalo et al. 2009, Lozinsky and Touchie 2018, Pasos et al. 2020, Sawyer 2014).

A case study for an SFH at CZ 5A indicates that the annual heating and cooling energy is reduced by 36% by delivering only the needed OA according to the 2007 edition of ASHRAE Standard 62.2 (ASHRAE 2007) with a dedicated outdoor air system (DOAS) instead of through the uncontrolled infiltration. Additionally, the required capacity of the geothermal heat pump (GHP) and the required size of the ground heat exchanger (GHE) are reduced by 30% and 16%, respectively. The reduced size of the GHP and GHE leads to a cost reduction, which may offset the expense for air sealing and the addition of a DOAS. Therefore, it is strongly recommended to include air sealing in a GHP retrofit because it can not only achieve deeper reduction in energy consumption and carbon emissions but also reduce the size and cost of GHP system. The reduced size of the GHP is critical in avoiding the winter peaking of electricity demand resulting from the electrification of space heating in buildings.

[43] https://sealed.com/resources/the-definitive-guide-to-air-sealing-your-house/

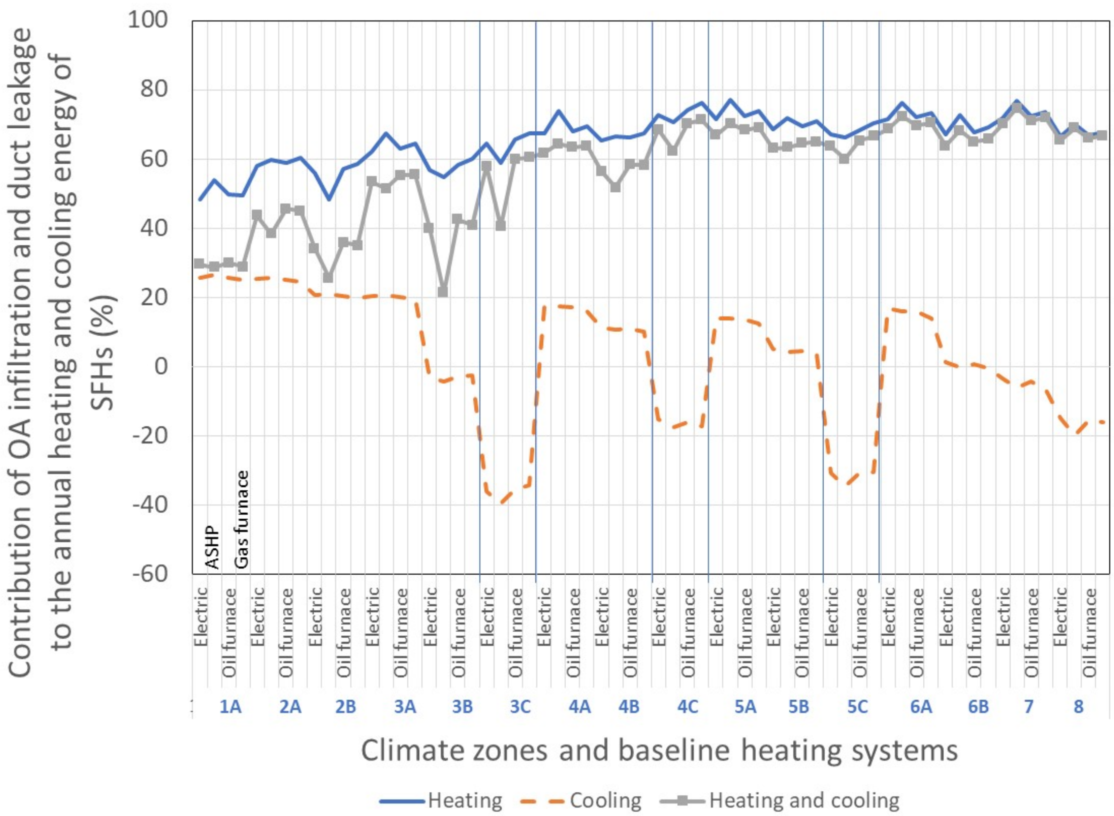


Figure C-2. Effects of OA infiltration and duct leakage on annual heating and cooling energy consumption of US Department of Energy prototype SFHs (designed following the 2006 edition of the IECC standard) at various CZs in the United States.

APPENDIX D. ADDITIONAL END-USE LOAD PROFILE DATA ANALYSIS

APPENDIX D. ADDITIONAL END-USE LOAD PROFILE DATA ANALYSIS

Table D-1. Characteristics of existing buildings included in NREL's end-use load profile database that are applicable for geothermal heat pumps (GHPs)

	Residential				Commercial			
	All	**GHP valid***	**With GHP system‡**	**%**	**All**	**GHP valid***	**With GHP system**	**%**
Number of housing units (10^6)	133.124	102.18	—	76.8	—	—	—	—
Floor space (10^6 ft^2)	234,458	185,937	—	79.3	54,942	41,908	1,059	76.3♦
Heating energy use (10^6 kWh) †	1,817,080	1,436,900	—	79.1	208,642	193,227	1,090	92.6♦
Cooling energy use (10^6 kWh) †	269,681	247,583	—	91.8	114,588	89,242	2,914	77.9♦

*Residential buildings that are applicable for GHP retrofit (excluding mobile homes, heating fuel none/other, cooling none); commercial buildings that are applicable for GHP retrofit (excluding district heating and/or cooling systems, GHP system, heating none, cooling none/evaporative)

♦ it is the percentage of commercial buildings that are included in NREL's end-use load profile database, which only accounts for 64% of existing commercial buildings in the US.

†Fan and pump energy excluded

‡No indication provided for residential buildings that already use a GHP

APPENDIX E. RELIABILITY ANALYSIS METHOD

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The calculated electricity demand with the geothermal heat pump (GHP) retrofit in 2021 was obtained by first calculating the demand reduction owing to the retrofit in 2021, and then subtracting it from the anticipated electricity demand in 2021. Because the end-use load profile data set does not include 2021 energy consumption data of individual balancing areas (BAs), researchers have proposed to calculate the demand reduction with the GHP retrofit based on available data in 2018 first, then forecasting the demand reduction of individual BAs in 2021 using a machine learning approach referred to as multilayer perceptron (MLP) (Suter 1990).

The detailed procedures of using MLP for forecasting the demand reduction in 2021 are as follows.

1. For the year of 2018, determine the ratios of the total building demand for individual BAs within the Electric Reliability Council of Texas (ERCOT). The *building demand ratio* is defined as the total building demand of a given BA to the total building demand of the ERCOT. Notably, the building demand accounts for most of the total demand in each BA. Without additional information on the nonbuilding demand of each BA, the building demand ratio is assumed to represent the ratio of the total demand of each BA to the total demand of the ERCOT.
2. Multiply the building demand ratio by the total demand of the ERCOT in 2018 to determine the total demand of each BA in 2018.
3. Determine the ratios of daily demand reduction for individual BAs in 2018. The daily demand reduction ratio is defined as the daily demand reduction of a given BA to the total daily demand of the same BA. The daily demand reduction is obtained by summing the hourly reduction, which can be obtained by the methodology described in Section 3.
4. Train the MLP by using the daily demand reduction ratios and weather conditions in 2018. Commonly considered weather conditions include average temperature, dew point, humidity, wind speed, and atmospheric pressure.
5. Apply the trained MLP to forecast the daily demand reduction ratio of each BA in 2021 with the weather conditions in 2021.
6. Determine the total demand of each BA in 2021 based on the building demand ratios in 2018 and the anticipated demand of ERCOT in 2021.
7. Multiply the forecasted daily reduction ratio by the total daily demand of each BA to determine the daily demand reduction of each BA in 2021.
8. Determine the total daily demand reduction of the ERCOT by summing the forecasted daily demand reduction of individual BAs.
9. Distribute the daily demand reduction of the ERCOT to each hour based on the ratio of hourly demand to the total daily demand of the same day.

In these steps, weather conditions are used as inputs for the MLP model because of their substantial effect on the electricity consumption of buildings. Cold and hot weather conditions necessitate the operation of heating and cooling systems, respectively, which contribute significantly to the overall electricity consumption of buildings. The correlation matrix between the average temperature and daily building electricity demand can be calculated based on the temperature data and electricity consumption data in 2018.