NATIONAL LABORATORY OF THE ROCKIES

ResStock Measure Documentation: Residential Two-Stage Geothermal Heat Pump (4.0 COP, 20.5 EER) With Envelope Improvements and Advanced Air Sealing

Jeff Maguire, Anthony Fontanini, Joseph Robertson, Yueyue Zhou, Philip White, and Jes Brossman

National Laboratory of the Rockies

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

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Technical Report
NLR/TP-5500-95035
June 2026

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List of Acronyms

COP	coefficient of performance
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EIR	energy input ratio
EMS	energy management system
GHP	geothermal heat pump
HVAC	heating, ventilation, and air conditioning

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List of Acronyms

ACCA	Air Conditioning Contractors of America
ACH	air changes per hour
Btu	British thermal units
COP	coefficient of performance
EER	energy efficiency ratio
GHP	geothermal heat pump
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code

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Executive Summary

The goal of this work is to develop energy efficiency, demand flexibility, and other retrofit end-use load shapes (electricity, gas, propane, or fuel oil) that cover a majority of the high-impact, market-ready (or nearly market-ready) measures. “Measures” refers to retrofits that can be applied to buildings during modeling.

An “end-use savings shape” is the difference in energy consumption between a baseline building and a building with an energy efficiency, demand flexibility, or other retrofit measure applied. It results in a time-series profile that is broken down by end use and fuel (electricity or on-site gas, propane, or fuel oil use) at each time step.

ResStock™ is a highly granular, physics-based, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the residential building stock across the United States. The baseline model intends to represent the U.S. residential building stock as it existed in 2018. Technical documentation for the inputs and assumptions in the baseline building stock model is available in Reyna et al. (2025). Calibration and validation of the baseline model results are available in the final technical report of the End-Use Load Profiles project (Wilson et al. 2022).

This document focuses on a single end-use savings shape measure: Residential Two-Stage Geothermal Heat Pump (4.0 COP, 20.5 EER) with Envelope Improvement and Advanced Air Sealing as a single package. As this package is a combination of multiple measures, this document focused on documenting the results associated with this combination of technologies, with individual measure documents for the two-stage geothermal heat pump and envelope improvements providing the information on the details of these measures. Envelope improvements combined with GHPs can modestly reduce energy consumption by a further 10-15%, as well as reduce the required size of the ground heat exchanger and heat pump by approximately 33% on average across the entire stock. The cost of installing envelope improvements in these homes is likely to be more than paid for by the reduction in equipment and drilling costs in these buildings for most of the stock. Utility bill and electric panel impacts are also presented and discussed.

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ResStock 2025 Release 1 Measure Documentation: Residential Two-Stage Geothermal Heat Pump (4.0 COP, 20.5 EER) with Envelope Improvements and Advanced Air Sealing

Accessing Results

This documentation covers the "Residential Two-Stage Geothermal Heat Pump (4.0 COP, 20.5 EER) with Envelope Improvements and Advanced Air Sealing" measure upgrade methodology and briefly discusses key results. All results can be accessed on the ResStock™ Open Energy Data Initiative End-Use Load Profiles for the U.S. Building Stock Data Lake and on the data viewer at resstock.nlr.gov.

Measure Summary

Table 1. Upgrade Measure Overview

Measure Title	**Residential Two-Stage Geothermal Heat Pump (4.0 COP, 20.5 EER) with Envelope Improvements and Advanced Air Sealing**
Measure Definition	This upgrade measure replaces the HVAC system in any existing dwelling unit in a building less than 8 stories with ducted heating or cooling with a two-stage compressor, water-to-air vertical ground heat exchanger geothermal heat pump (GHP) with a variable speed fan. The measure also adds some improvements to the envelope, including increasing attic insulation, general air sealing of the living space, and duct sealing plus insulation.
Applicability	This measure applies to all dwellings with: - Non-shared (in-unit) HVAC and any of the following heating fuels: electricity, natural gas, fuel oil, or propane - Shared (across multiple units) HVAC and a building height of < 8 stories and any of the following heating fuels: electricity, natural gas, fuel oil, or propane - Dwelling units with air ducts - Dwelling units with soil thermal conductivity greater than 0.8 Btu/h-ft-°F With these applicability constraints, the measure upgrade applies to **71%** of the existing residential building stock. **6.4%** of the residential units that receive the GHP upgrade lack existing space cooling systems in the baseline.
Not Applicable	This measure does not apply to dwelling units: - Shared HVAC (across multiple units) in high-rise (≥8 floors) buildings. - Dwelling units without air ducts These constraints exclude **25%** of the building stock from receiving this measure upgrade. An additional 4% of the dwelling units do not receive this upgrade because of their heating fuel type.
Original Release Project Configuration File(s)	2025 Release 1: 2025/resstock_amy2018_release_1 ResStock's 2025 Standard Data Release 1 (SDR) project file.

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1 Technology Summary

This measure combines two separate measures into a single package. The first measure is a water-to-air geothermal heat pump (GHP) with a two-stage compressor rated at a COP of 4.0 and an EER of 20.5. More details on GHPs and how they are modeled in ResStock, including the details of modeling the ground heat exchanger, are included in the single-stage GHP measure document[1]. The details of how two-stage GHPs with this rated efficiency are modeled are included in the two-stage GHP measure document[2]. The details of the envelope improvement measure are included in the air sealing, attic insulation, and duct sealing improvement measure document[3].

In some cases, it may be more cost effective to both do envelope improvements and install a GHP at the same time as the envelope improvements reduce the required size of the GHP and the ground heat exchanger, therefore reducing the cost of the GHP retrofit. Refer to the package or individual improvement documents for more details on each individual measure.

[1] https://docs.nlr.gov/docs/fy26osti/95032.pdf
[2] https://docs.nlr.gov/docs/fy26osti/95034.pdf
[3] https://docs.nlr.gov/docs/fy26osti/96347.pdf

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2 Modeling Approach

2.1 Applicability of Two-Stage GHP

Using the same applicability criteria as the single-stage GHP and the stand-alone two-stage compressor, water-to-air vertical ground heat exchanger GHP upgrade measure applies to all dwellings with:

- Non-shared (in-unit) HVAC and any of the following heating fuels: electricity, natural gas, fuel oil, or propane
- Shared (across multiple units) HVAC and a building height of < 8 stories and any of the following heating fuels: electricity, natural gas, fuel oil, or propane
- Dwelling units with ducts
- Dwelling units with soil thermal conductivity greater than 0.8 Btu/hr-ft-°F

With these applicability constraints, the measure upgrade applies to roughly 71% of the existing building stock. 6.4% of the residential units that receive the GHP upgrade lack existing space cooling systems in the baseline.

Applicability of this measure upgrade is based on ResStock housing characteristics that determine the available options and the options' details (Reyna, et al., 2025). Specifically, the "HVAC Heating Efficiency" characteristic in ResStock is used to apply each respective heat pump option. "HVAC Has Ducts" describes the presence of ducts in the dwelling. "Heating Type" describes the baseline heating fuel of the dwelling. "HVAC Shared Efficiencies" describes the shared HVAC system of the dwelling, if applicable. "Geometry Building Type Height" describes the height and building type of the dwelling. More information on the ResStock housing characteristics can be found in the ResStock Technical Reference Guide[4].

2.2 Applicability of Envelope Improvements

While envelope improvements are included for any home receiving a two-stage GHP, the baseline conditions must warrant an improvement for each component of the upgrade to apply. For example, homes that already are tightly sealed will not have air sealing applied.

For air sealing upgrades to apply, the baseline home must have 6 or more air changes per hour (ACH). The upgrade case is then air sealed to reach 5 ACH50. More details on air sealing applicability can be found in the air sealing measure document[5].

For duct sealing and insulation, the upgrade case installs R-6 duct insulation if ducts have R-4 or less insulation. Ducts are sealed to 5% leakage if there is more than 6% leakage. These improvements can be installed independently of each other, or both may apply if both the leakage and insulation criteria are met. More details on duct sealing and insulation applicability can be found in the duct improvement measure document[6].

[4] https://docs.nlr.gov/docs/fy25osti/91621.pdf
[5] https://docs.nlr.gov/docs/fy26osti/96738.pdf
[6] https://docs.nlr.gov/docs/fy26osti/96344.pdf

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For attic insulation, this measure upgrades attic floor insulation in unfinished attics where the existing R-value falls at least R-10 value below the maximum level recommended by the IECC for each unit's climate zone. The post-retrofit R-value is set to reflect the maximum value recommended by code, while still aligning with outcomes observed in empirical studies. For example, while the IECC recommends an R-value range of R-49 to R-60 for Climate Zone 2, dwelling units in this zone are upgraded to R-60 to represent the upper bound of achievable performance. This approach ensures that the modeled retrofit captures both the energy savings potential of code-compliant upgrades and the levels typically achieved in field implementations. More details on attic insulation applicability can be found in the attic insulation measure document[7].

2.3 OpenStudio-HPXML Overview

The ResStock building stock energy model contains conditional probability distributions of building characteristics that are representative of the contiguous U.S. residential building stock [7]. These are sampled to create a synthetic stock where each sample has an assigned option for each characteristic for each dwelling unit to be simulated. ResStock utilizes the OpenStudio-HPXML workflow to translate these dwelling characteristics into building models ready to be simulated via OpenStudio and EnergyPlus through the use of an HPXML file. For reference, the state of the OpenStudio-HPXML repository when the ResStock 2025 Release 1 dataset was created can be found here. Assumptions about the GHP upgrades that are not explicitly defined in ResStock are taken care of in the BuildResidentialHPXML measure.

For information on how OpenStudio-HPXML handles controls in ResStock Dataset 2025 Release 1 see here, and for how it handles HVAC distribution see here. Additional details regarding applying the two-stage GHP measure are included in the relevant section of that measure document.

2.4 Relevant Two-Stage Water-to-Air Vertical Ground Heat Exchanger GHP Upgrade Details

Details specific to the two-stage GHP that may interact with the envelope improvements are included below. In many cases, the approach used here is the same as when two-stage GHP equipment is installed on its own, but relevant portions of that approach are reiterated here to remind readers of the specifics. Since envelope improvements can change the loads and size of equipment installed, this reiteration focuses on the approach to sizing equipment

2.4.1 GHP Sizing Methodology

The two-stage GHP uses the same sizing methodology as the single-stage GHP. The design heating and cooling loads are calculated in accordance with Air Conditioning Contractors of America (ACCA) Manuals J (ACCA, 2016), and the equipment size is selected based on ACCA Manual S (ACCA, 2014) using a routine included in OpenStudio-HPXML. Note that because the GHP sizing routine includes accounting of the peak heating and cooling building loads, equipment sizes are decreased when envelope improvements are included. This means that for

[7] https://docs.nlr.gov/docs/fy26osti/96739.pdf

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the combined package the equipment capacity, ground heat exchanger size, and associated cost for installing a GHP are all reduced compared to just installing a two-stage GHP.

Why sizing around envelope improvements matters:
When the building envelope is improved (through measures such as added insulation, air sealing, or high-performance windows) the peak heating and cooling loads are reduced. This directly impacts the sizing calculation for the GHP, allowing for smaller-capacity equipment to meet the same comfort requirements and reducing the capital costs for the heat pump. Smaller systems also require less ground heat exchanger length, which further lowers installation costs and can improve system efficiency. By addressing the envelope before or during GHP sizing, the project avoids oversizing, reduces upfront and operating costs, and maximizes the long-term performance of the system. The cost savings for the GHP system can potentially be larger than the cost of installing envelope improvements, leading to a lower overall first cost, depending on the local costs of the heat pump and drilling.

Note that because the sizing routine accounts for the peak heating and cooling building loads, equipment sizes are decreased when envelope improvements are included. This means that for the combined package, the equipment capacity, ground heat exchanger size, and the associated cost for installing a GHP are all reduced compared to just installing a two-stage GHP.

2.4.2 Geothermal Ground Heat Exchanger

The two-stage GHP uses the same type of ground heat exchanger as the stand-alone two-stage GHP measure. Both use thermally enhanced grout and pipe materials to improve heat transfer, and the loop is installed in a vertical, rectangular configuration.

Why the ground heat exchanger matters when discussing envelope improvements:
The ground heat exchanger is one of the largest cost components of a GHP system because drilling and installing the vertical loops is labor- and equipment-intensive. When the building envelope is improved, the heating and cooling loads are reduced, which means the GHP can be smaller. A smaller GHP requires less heat exchange with the ground, allowing for shorter ground heat exchangers. This reduction in drilling length can significantly cut installation costs and make the overall system more affordable. In short, better insulation and air sealing do not just shrink the equipment size, they also shrink the number of vertical feet you need to drill.

2.5 Attic Insulation, Air Sealing, and Duct Sealing

Each individual component of this measure is both documented separately as well as being documented as a package[8], with the package document linking to individual component documents. The goal of this package is to capture efficiency measures that are reasonably likely to be applied for existing buildings. This is similar in spirit to what might be done as part of weatherization upgrades to a home, where the easiest and most beneficial improvements are performed.

This upgrade package integrates three coordinated energy efficiency measures: air sealing, attic floor insulation, and duct sealing, to address different but related sources of energy loss in a home. Air sealing targets gaps, cracks, and penetrations in the building envelope to reduce

[8] https://docs.nlr.gov/docs/fy26osti/96347.pdf

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uncontrolled air leakage, improve comfort, and lessen the workload on heating and cooling systems. Attic floor insulation slows heat transfer between living areas and unconditioned attic spaces, keeping heat inside in winter and out in summer. Duct sealing prevents conditioned air from escaping into unconditioned spaces through leaky ducts, improving HVAC efficiency, maintaining more even indoor temperatures, and protecting indoor air quality. While each measure provides benefits individually, their combined effect is significantly greater, making them most effective when implemented as a package.

The recommended implementation sequence is based on building science principles: first air sealing to achieve a target of 5 ACH50, then duct sealing and insulating to reduce leakage to a maximum of 5% and achieve R-8 duct insulation, and finally upgrading attic floor insulation. This order ensures air leaks are addressed before insulation is installed, prevents ducts from being buried before sealing, and optimizes the performance of both insulation and the HVAC system. By following this sequence, field staff can more easily identify and seal problem areas and avoid rework.

Together, these measures improve comfort, lower energy bills, and enhance indoor air quality throughout the year. Air sealing stabilizes indoor temperatures and minimizes drafts, duct sealing reduces waste and protects against contaminants entering the system, and attic insulation locks in the conditioned air for longer periods. When applied in concert, they create a tighter, better-insulated, and more efficient home, with benefits that are greater and more durable than any single measure alone.

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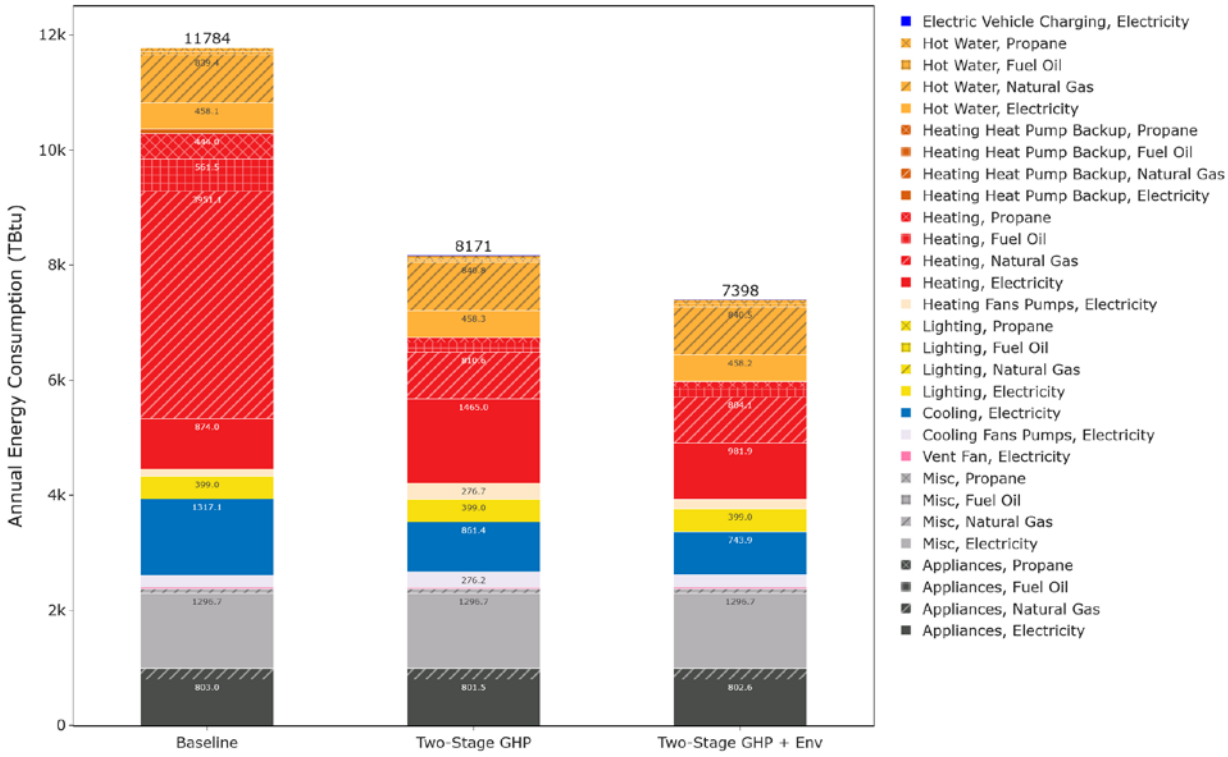
3 Results

3.1 Annual Stock Savings

Figure 1 shows the annual energy consumption for baseline, two-stage GHP, and two-stage GHP plus envelope improvements. The top figure shows the results for all dwellings, regardless of whether the measure applies, while the bottom figure only shows results for applicable portions of the housing stock. Results for the whole stock are relevant for some groups, such as utilities, who might care how the total load changes in their service territory with the understanding that this measure will not improve all houses. Results that focus only on the applicable portion of the stock make it easier to understand how this measure affects energy use directly. Note that for this measure about 18% of the stock does not have a GHP measure apply, largely due to a lack of ducts in the baseline building. Adding envelope improvements increases the amount of energy savings over just installing a two-stage GHP by about 10% for the entire housing stock and about 13% for the portion of the stock that can receive a GHP upgrade. While both heating and cooling energy consumption are reduced, most of the savings come from reducing heating energy use as the U.S. housing stock overall is heating dominated.



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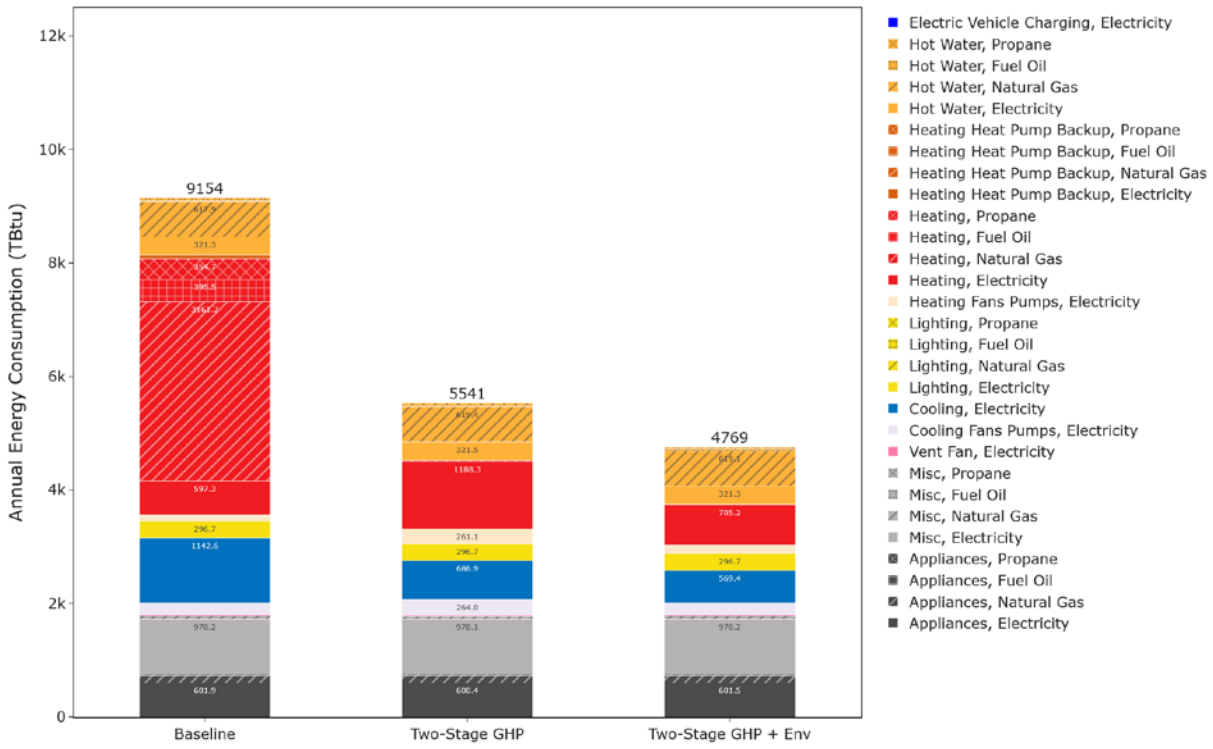

Figure 1. Annual energy consumption of dwellings in the baseline and with two-stage GHP upgrades and two-stage GHP plus envelope upgrades.

The top figure shows all dwellings, including those the GHP upgrade may not apply to, while the bottom figure is filtered to only show applicable buildings in both the baseline and upgrade scenario.

Figure 2 shows the annual energy consumption for the portion of the housing stock this upgrade applies to split out by Building America climate zone (Antonopoulos, Gilbride, Margiotta, Cragin, & Kaltreider, 2022). As envelope improvements reduce loads, some savings are seen in almost all climate zones. The one exception is the marine climate zone, which sees a slight increase as the higher infiltration can sometimes reduce HVAC energy consumption during very mild conditions. The largest incremental increase in savings is seen in cold climate zones, which also have the largest portion of the housing stock. The reduction in heating load and associated energy consumption provides most of the savings in these climate zones. Note that for all climate zones installing a two-stage GHP provides most of the savings, while additional envelope improvements further increase the savings.

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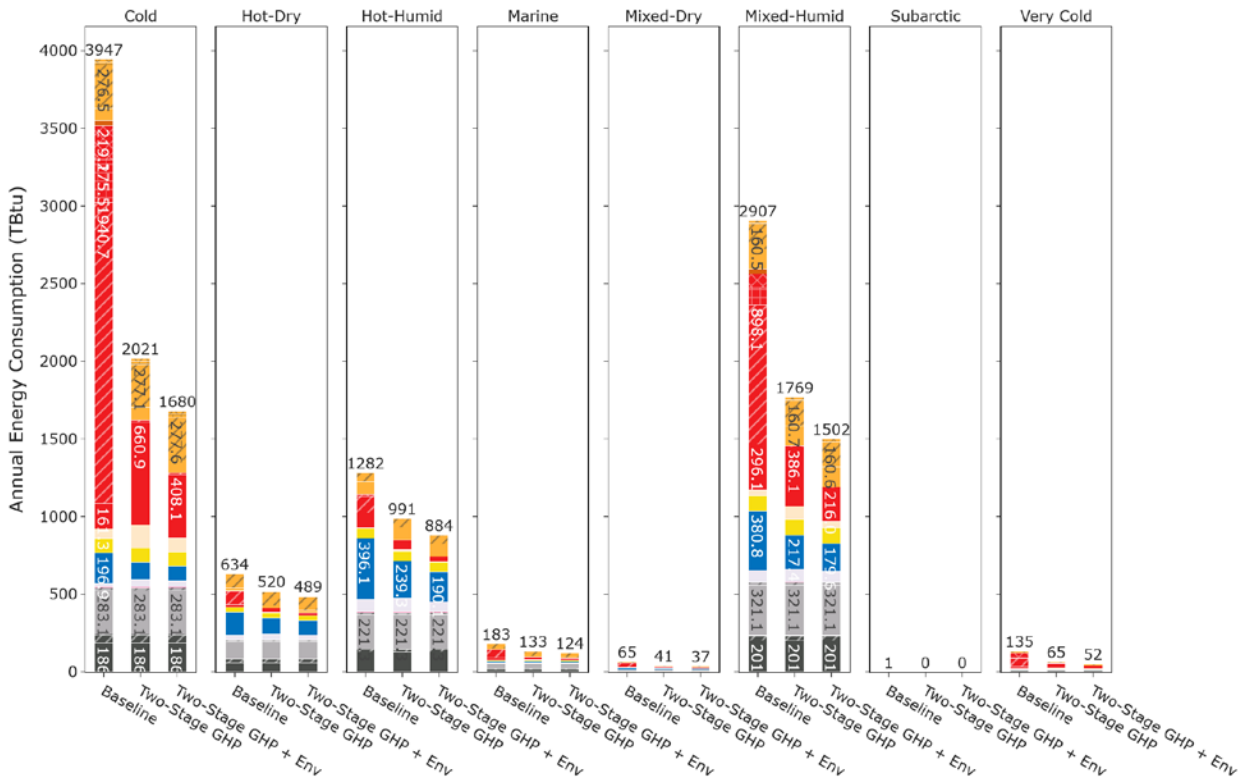

Figure 2. Annual energy consumption of dwellings in the baseline and with two-stage GHP upgrades and two-stage GHP plus envelope upgrades by climate zone.

Figure 3 shows the annual energy consumption subdivided based on the baseline heating fuel. Cases with existing electric heating are generally replacing electric resistance equipment, such as an electric furnace, with a more efficient GHP. Note that because ducts are required in the baseline for this upgrade to apply, homes with electric baseboards are excluded here. The largest absolute savings occurs in homes that use natural gas for heating, which also make up most of the applicable housing stock. Adding envelope improvements on top of installing a two-stage GHP can further increase energy savings by 10-15% depending on the baseline heating fuel.

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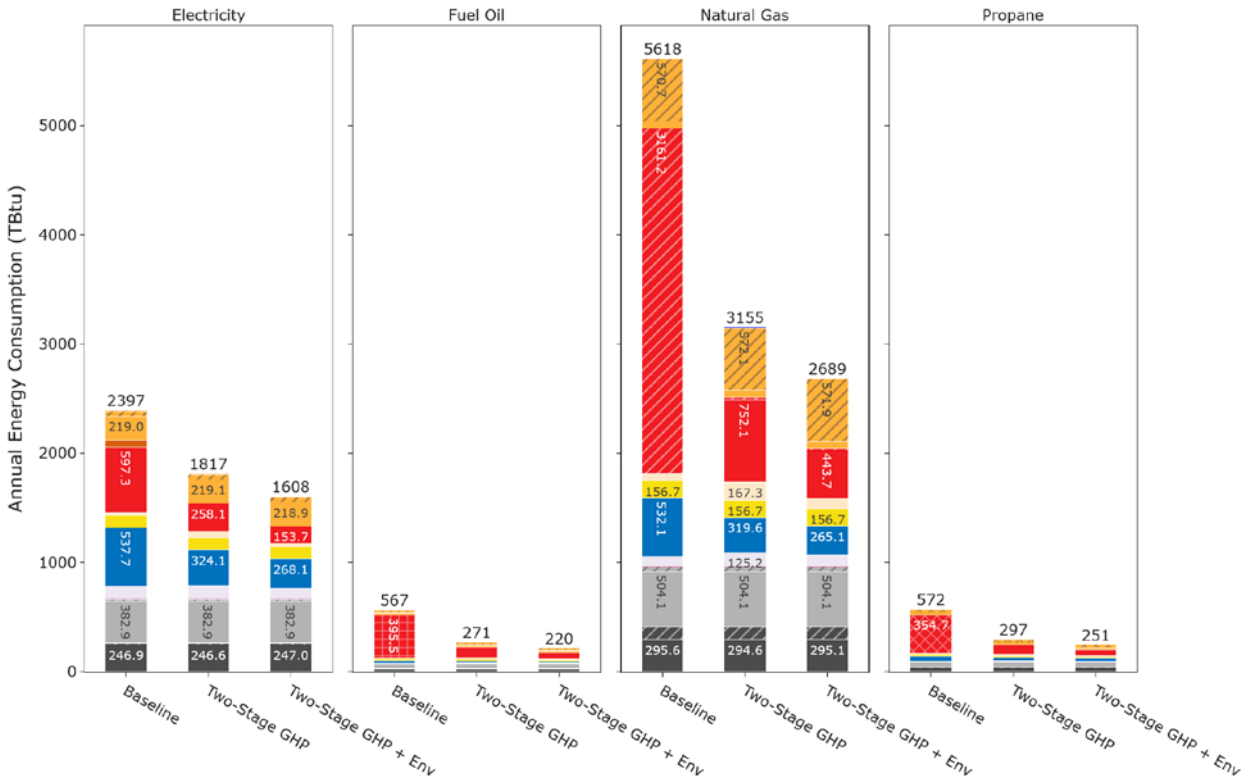

Figure 3. Annual energy consumption of dwellings in the baseline and with two-stage GHP upgrades and two-stage GHP plus envelope upgrades by baseline heating fuel.

3.2 Annual Energy Bill Impact, Applicable Dwelling Units Only

Energy bills for applicable dwelling units only are shown below in the following figures. On average, energy bills decreased 27% for the variable speed GHP compared to baseline dwelling units. This is a greater percent savings than the single-stage GHP at 3% savings, double the two-stage GHP which was 11% savings, and the variable speed GHP which had 24% savings. The average energy bill for the two-stage GHP with envelope improvements and advanced air sealing is shown in Figure 4. All fuel costs decreased on average.

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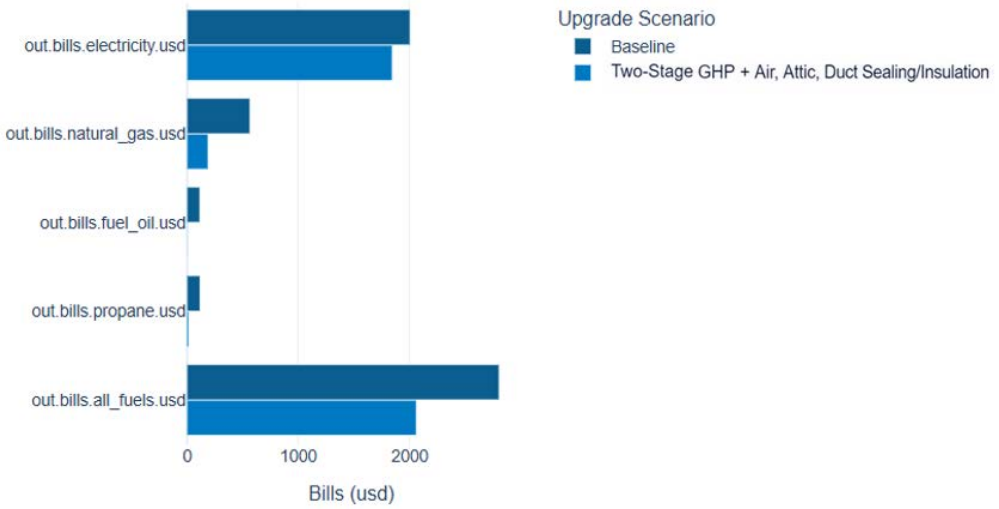

Figure 4. Average annual energy bill broken out by fuel type for dwelling units that receive the two-stage GHP with envelope improvements and advanced air sealing

Figure 5 shows that the average two-stage GHP with envelope improvements and advanced air sealing and advanced air sealing energy bill is 3.4% less than the variable speed GHP, 13.9% less than the two-stage GHP, and 24% less than the single-stage GHP.

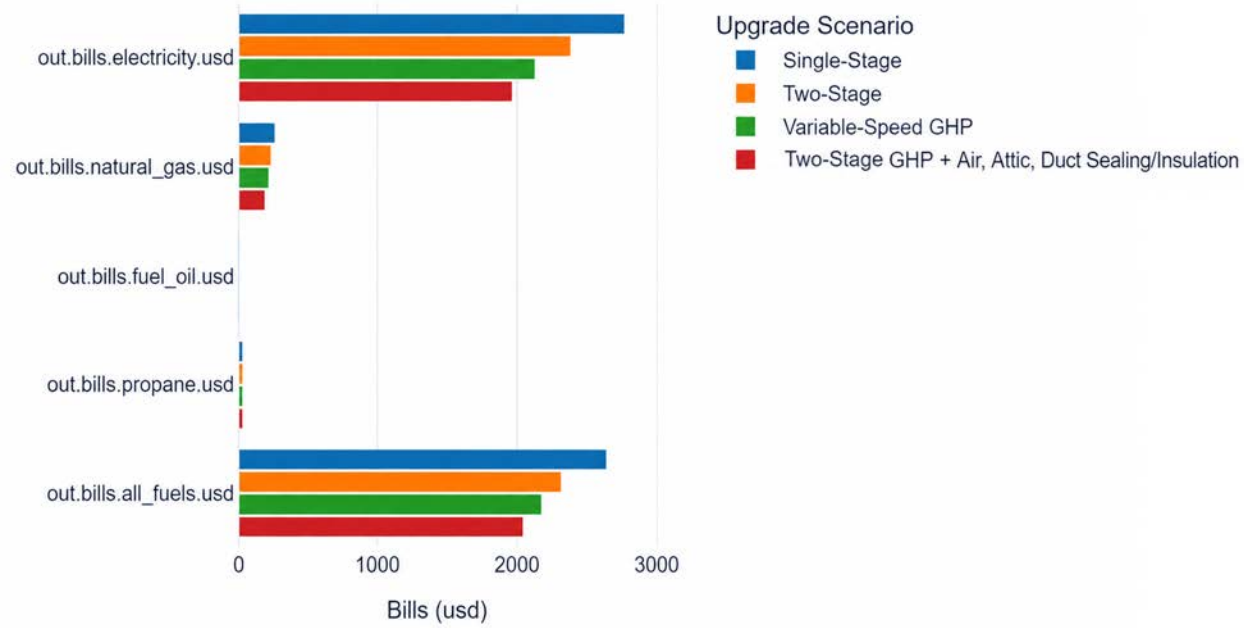

Figure 5. Average annual energy bill comparison between single-stage GHP, two-stage GHP, variable speed GHP, and two-stage GHP with envelope improvements and advanced air sealing broken out by fuel type for applicable dwelling units only

Figure 6 shows average energy bills broken out by Building America climate zone. The two-stage with envelope improvements and advanced air sealing results in a lower average energy bill across all climate zones.

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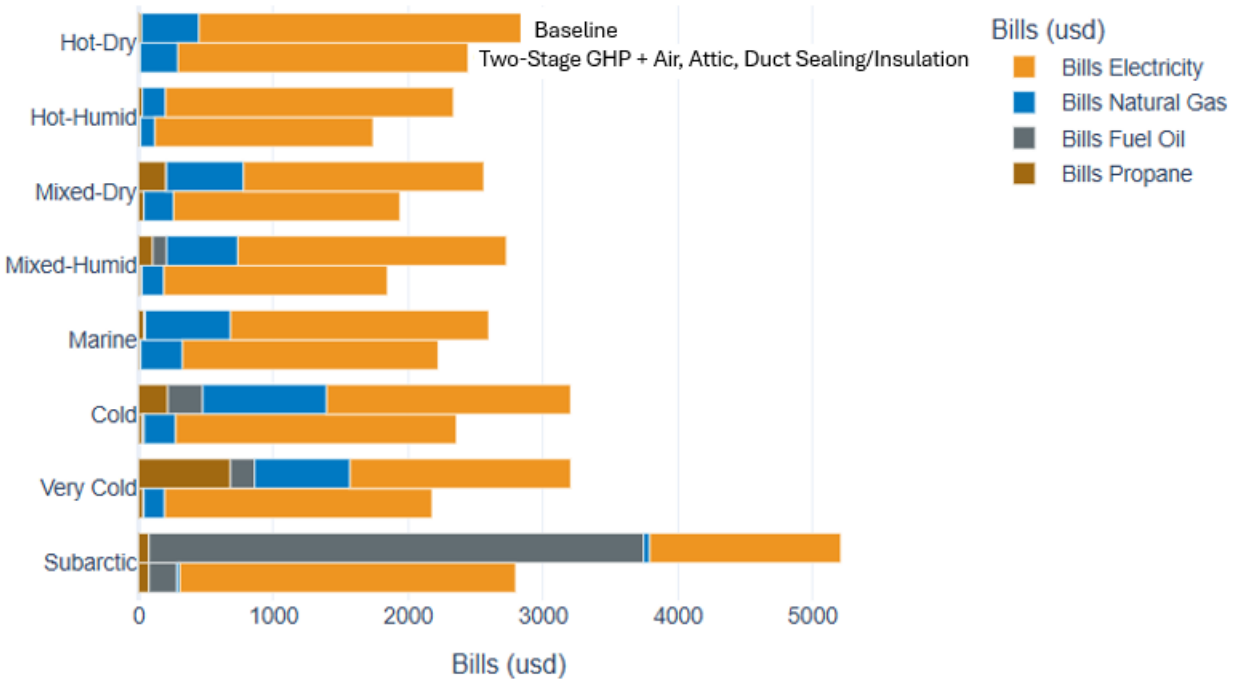

Figure 6. Average annual energy bill broken out by Building America climate zone for applicable dwelling units only

Figure 7 shows a comparison of four GHP upgrades. Two-stage with envelope improvements and advanced air sealing has the lowest average energy bill in six of the eight Building America climate zones, with most of the savings from electricity.

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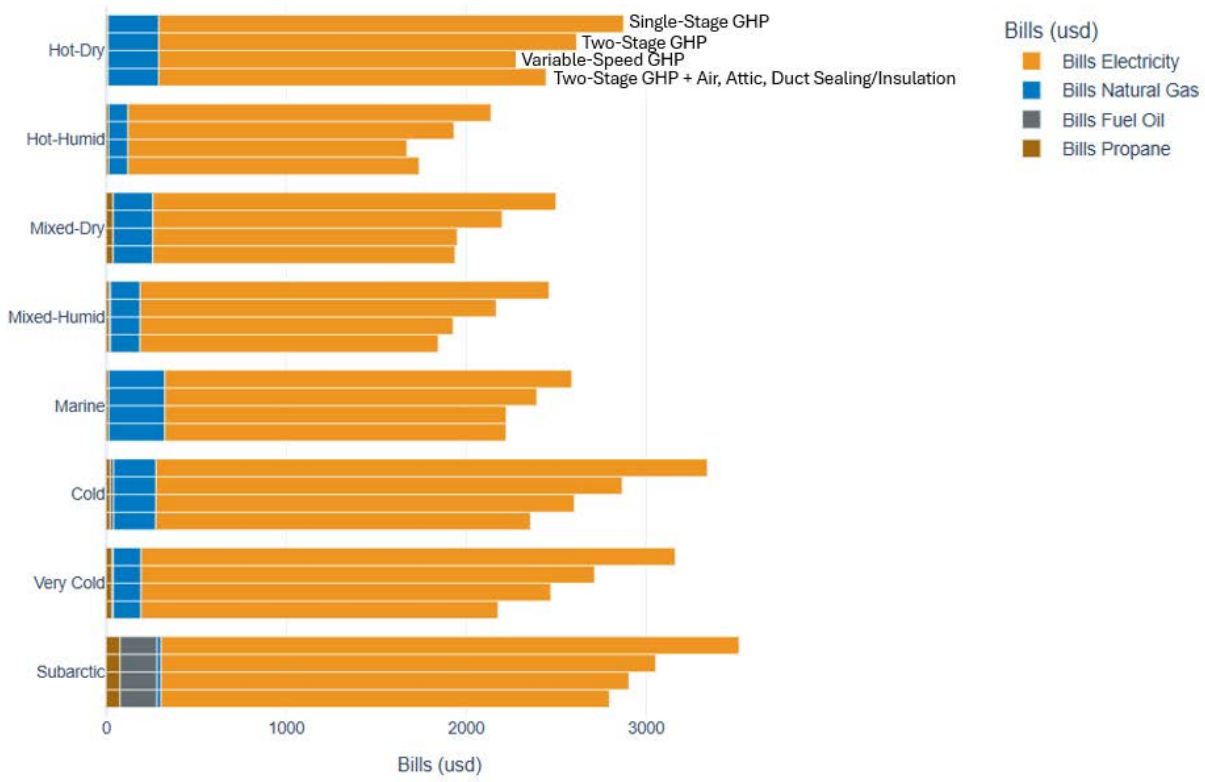

Figure 7. Average annual energy bill comparison broken out by Building America climate zone for single-stage GHP, two-stage GHP, variable speed GHP, and two-stage GHP with envelope improvements and advanced air sealing

3.3 Ground Heat Exchanger Length Impact from Envelope Improvements

Figure 8 shows the total average length of the ground heat exchanger for cases with and without envelope improvements. The length here is calculated based on the number of boreholes installed multiplied by the average borehole depth. As envelope improvements reduce both annual energy use and peak loads, the envelope improvements have an additional benefit of reducing the peak loads and the associated size of the heat pump, as well as the amount of drilling required for the ground heat exchanger. Reductions in the length of the ground heat exchanger average 33%, showing that maximum potential benefit can be achieved by installing both GHPs and envelope improvements in tandem. While the cost effectiveness of individual installations will change based on building loads, local utility rates, drilling costs, and other factors, this combined package shows a strong potential for being a more cost-effective path as GHP installation, particularly drilling costs, is much more expensive than installation of the envelope improvements included here.

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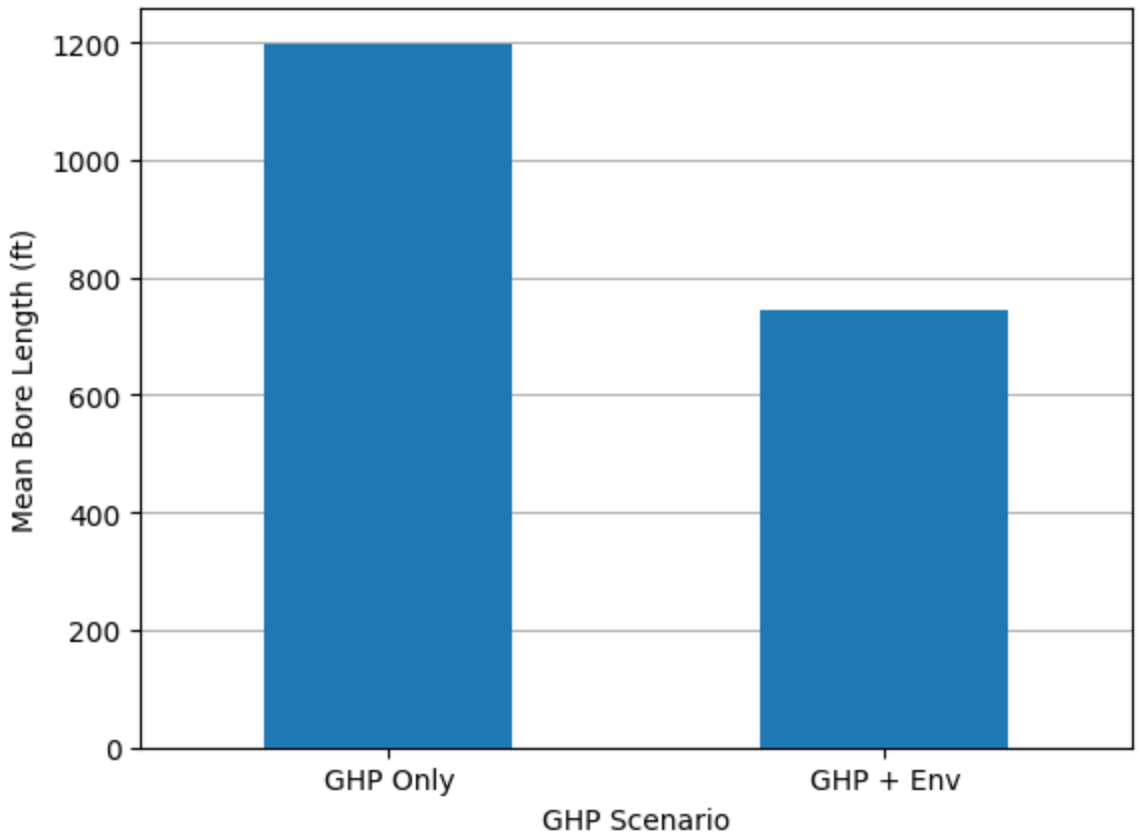

Figure 8. Average total length of ground heat exchanger for two-stage GHPs with and without envelope improvements and advanced air sealing across the applicable portion of the stock.

3.4 Two-Stage GHP Sizing Impacts from Envelope Improvements

Figure 9 shows the average HVAC capacity for two-stage GHPs with and without envelope improvements being included. As with the ground heat exchanger length, the size of HVAC equipment is very influenced by the loads in the building, and envelope improvements can substantially reduce the required capacity. This also presents substantial cost savings. While the ground heat exchanger installation costs are generally much larger than the cost of the heat pump, this can also represent some cost savings when installing a GHP system where the costs of installing both envelope improvements and a GHP might end up having a lower overall first cost as the lower GHP installation costs more than offset the cost of envelope improvements.

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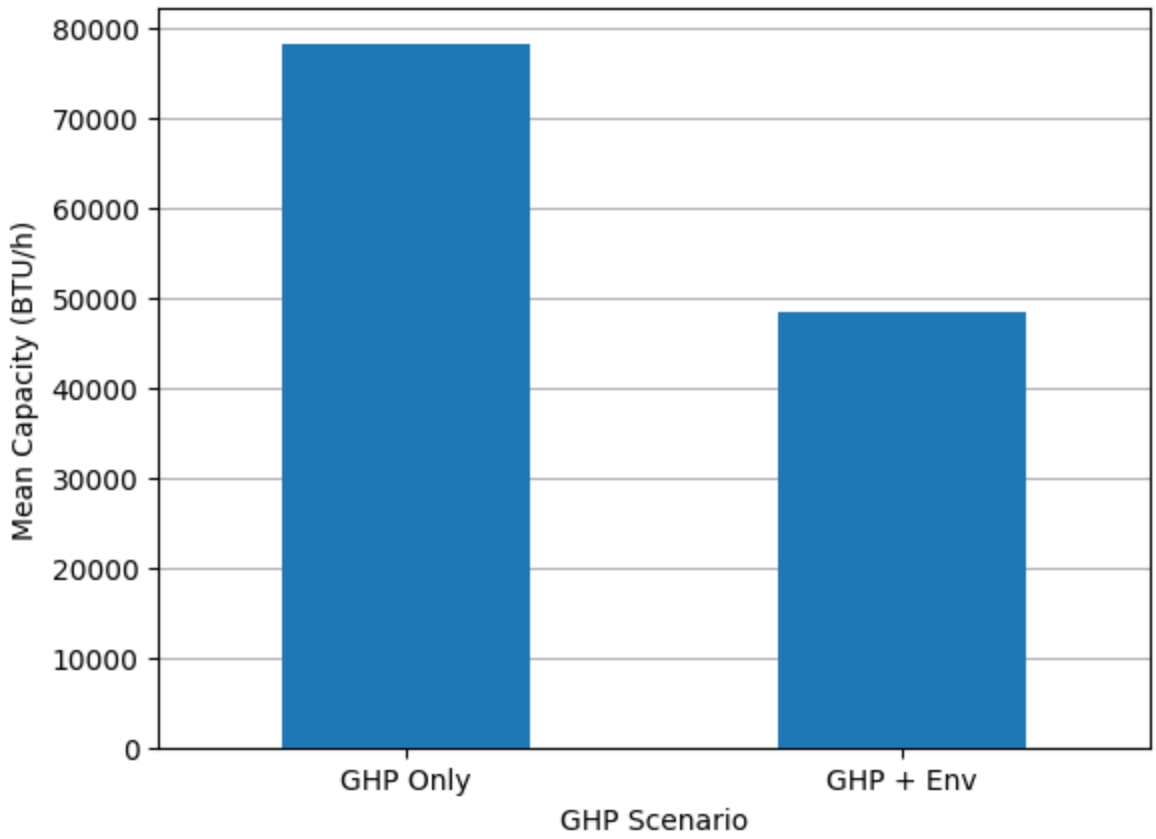

Figure 9. Average heating and cooling capacity for two-stage GHPs with and without envelope improvements and advanced air sealing across the applicable portion of the stock.

3.5 Electric Panel Impact

This section details the impact the two-stage GHP with envelope improvements and advanced air sealing will have on electrical panels. The modeling assumptions and details about electric panels in ResStock can be found in the single-stage GHP documentation[9].

First, Figure 10 and Figure 11 show information about the ResStock 2025 Release 1 baseline housing stock electric panel distribution. Figure 10 shows in the first column, "All", that about 35% of all dwelling units have 0 or only 1 breaker space available. Figure 11 shows in the first column that 97.7% of electric panels have no existing capacity constraint for the baseline housing stock, but that the other 2.3% of electric panels already have an existing capacity constraint.

Capacity constraints in the existing baseline stock are due in part to the uncertainty associated with the modeling process, where the prediction of the panel size is not based on the presence of all major electric appliances. However, it's important to recognize that this level of uncertainty applies to all panel results, including those that look reasonable. Hence, the capacity constrained

[9] https://docs.nlr.gov/docs/fy26osti/95032.pdf

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homes in the baseline can be thought of as over-capacity homes that experience frequent flickering of lights or tripping of breakers if/when large appliances are turned on.

Before this two-stage GHP with envelope improvements and advanced air sealing retrofit would take place, the panels experiencing a capacity constraint would likely need to address this issue first. Users are encouraged to alternatively analyze the constraint outcomes by excluding homes whose pre-existing capacity constraint is not worsened by the upgrade.

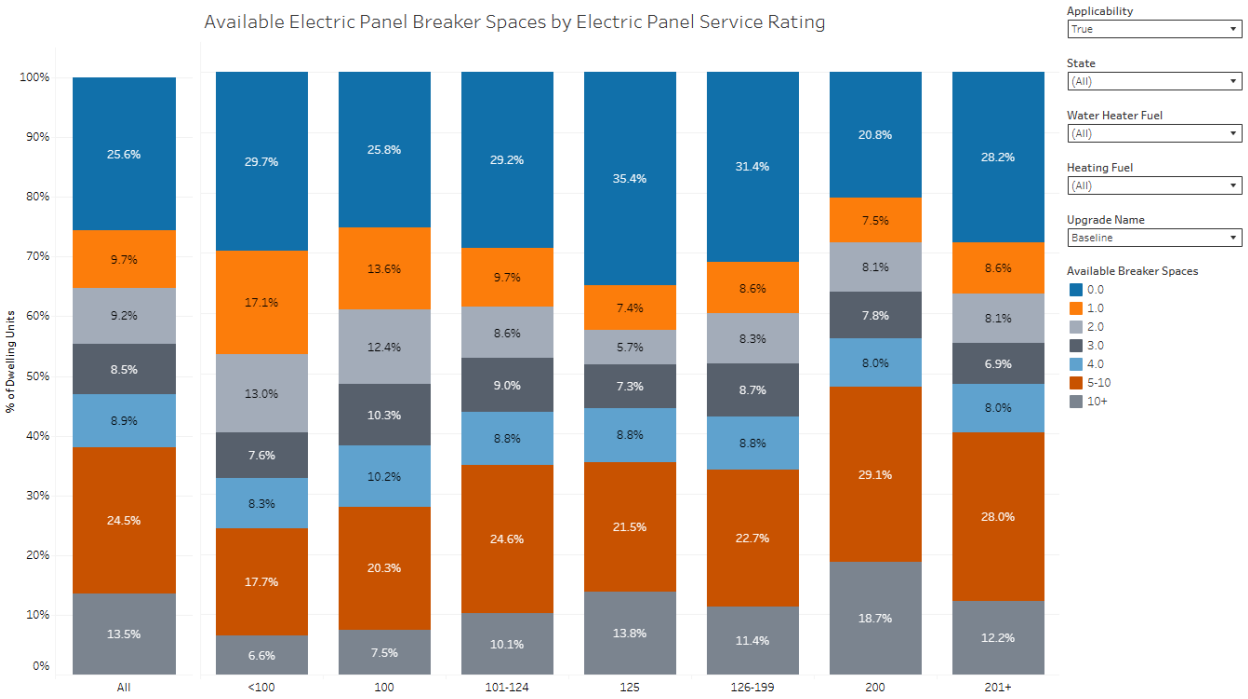

Figure 10. Baseline electric panel breaker spaces by electric panel service rating

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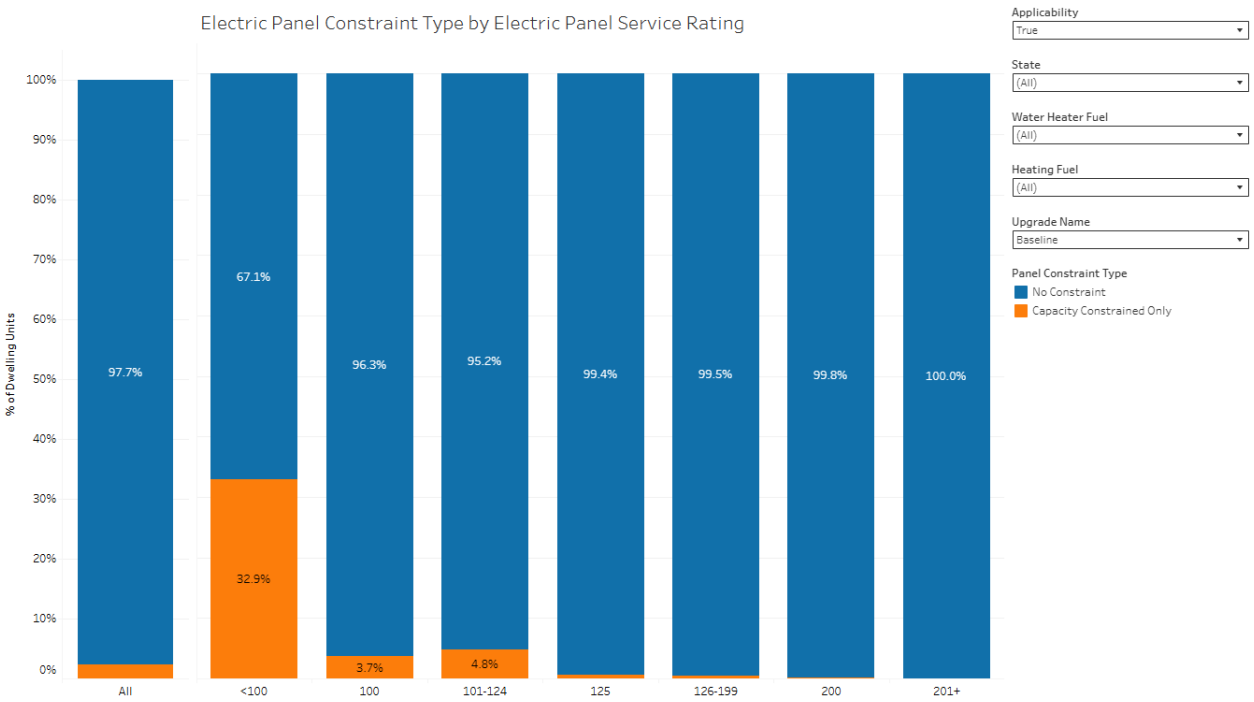

Figure 11. Baseline electric panel constraint type by electric panel service rating

Figure 12 shows the distribution of panel constraints overall, see the first column, and then by heating fuel for dwelling units that receive the two-stage GHP with envelope improvements and advanced air sealing. It is estimated that about 27% of dwelling units upgrading to a two-stage GHP with envelope improvements and advanced air sealing will experience either a capacity and/or space constraint, and the other 73% will experience no constraint. Looking more closely at the results, and understanding that natural gas is the predominant heating fuel across the U.S. as seen in Figure 3, these results are heavily weighted by dwelling units that have natural gas as their original heating fuel.

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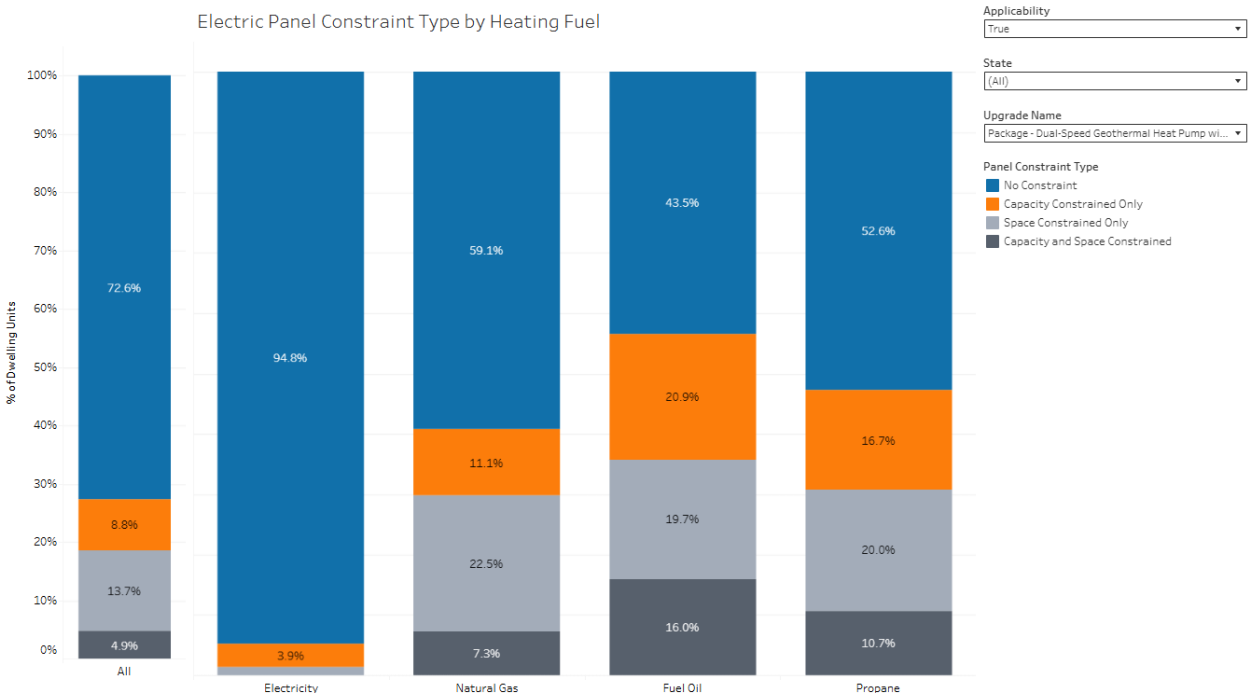

Figure 12. Distribution of panel constraints by heating fuel

The next three figures show percentages of dwelling units for each state that would have some type of electric panel constraint after the two-stage GHP with envelope improvements and advanced air sealing. Figure 13 shows a range of 5-61% of dwelling units that would have either a capacity and/or space constraint after the two-stage GHP with envelope improvements and advanced air sealing. Specifically looking at space constraints, Figure 14 shows a smaller range from about 2% to 47% of dwelling units that would have a space constraint. Finally, Figure 15 shows a range of roughly 3% to 35% of dwelling units would have a capacity constraint.

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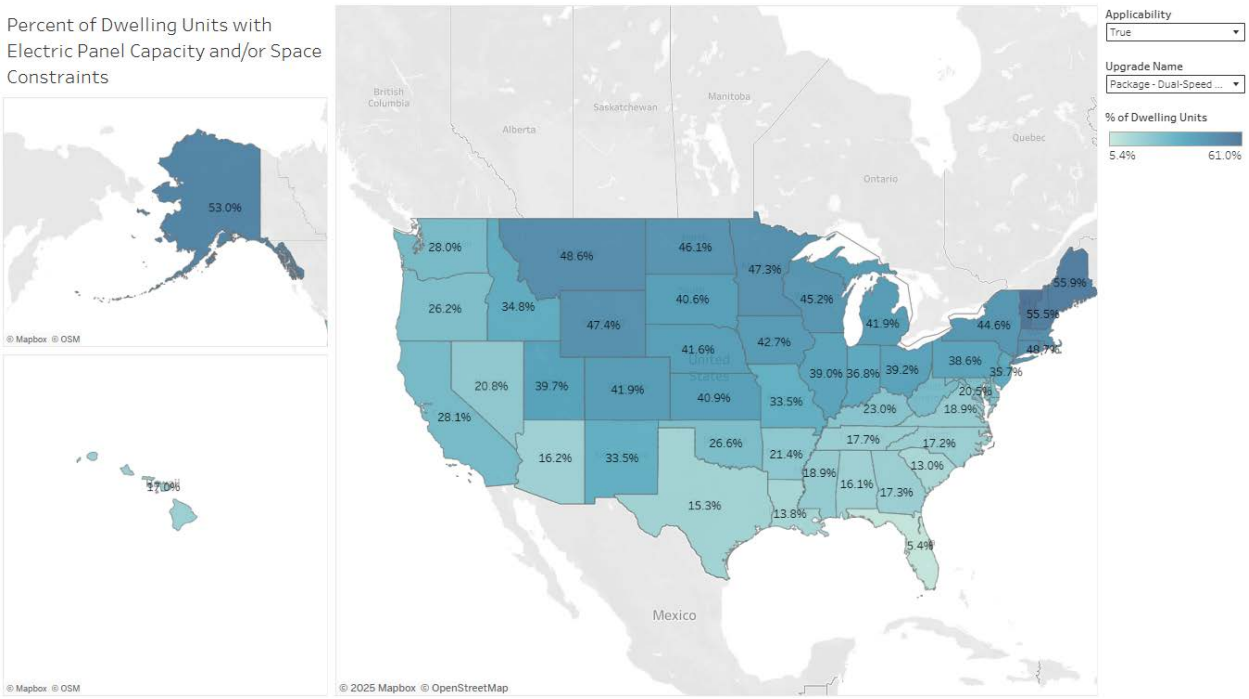

Figure 13. Percent of dwelling units with an electric panel constraint (capacity and/or space) by state after a two-stage GHP with envelope improvements and advanced air sealing

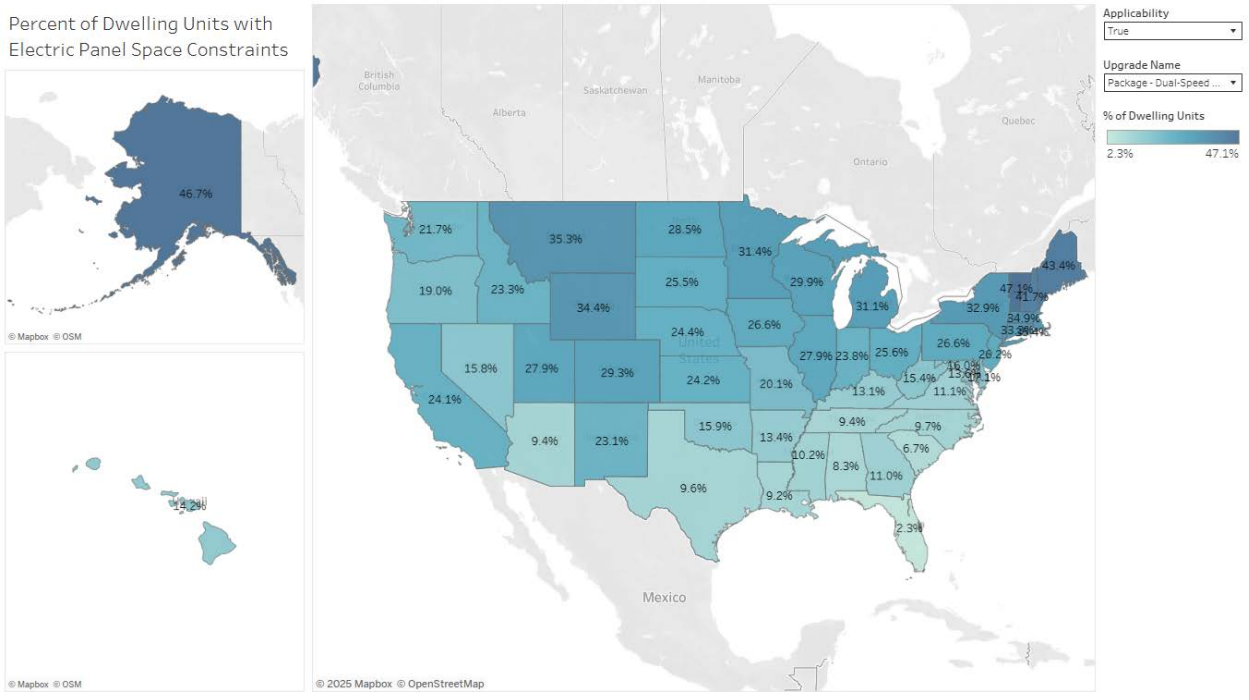

Figure 14. Percent of dwelling units with an electric panel space constraint by state after a two-stage GHP with envelope improvements and advanced air sealing

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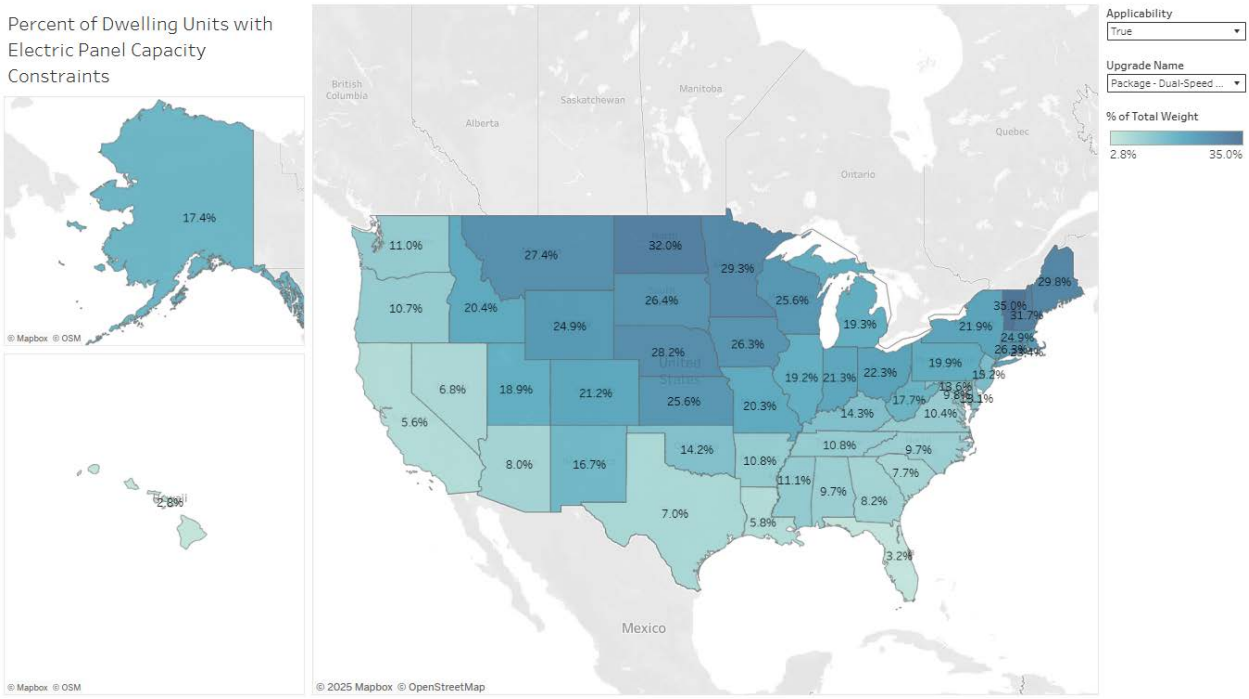

Figure 15. Percent of dwelling units with an electric panel capacity constraint after a two-stage GHP with envelope improvements and advanced air sealing

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