

Appendix: Methodology and Approach

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1. Overview

This document lays out the methodology used to quantify the impacts of geothermal heat pump (GHP) adoption including demand-side modeling, utility system savings, customer bill savings, incremental GHP costs, and emissions savings. It provides additional detail on the data sources, assumptions, and analytical methods underlying the results presented in the main report.

Exhibit 1: Analytical Framework

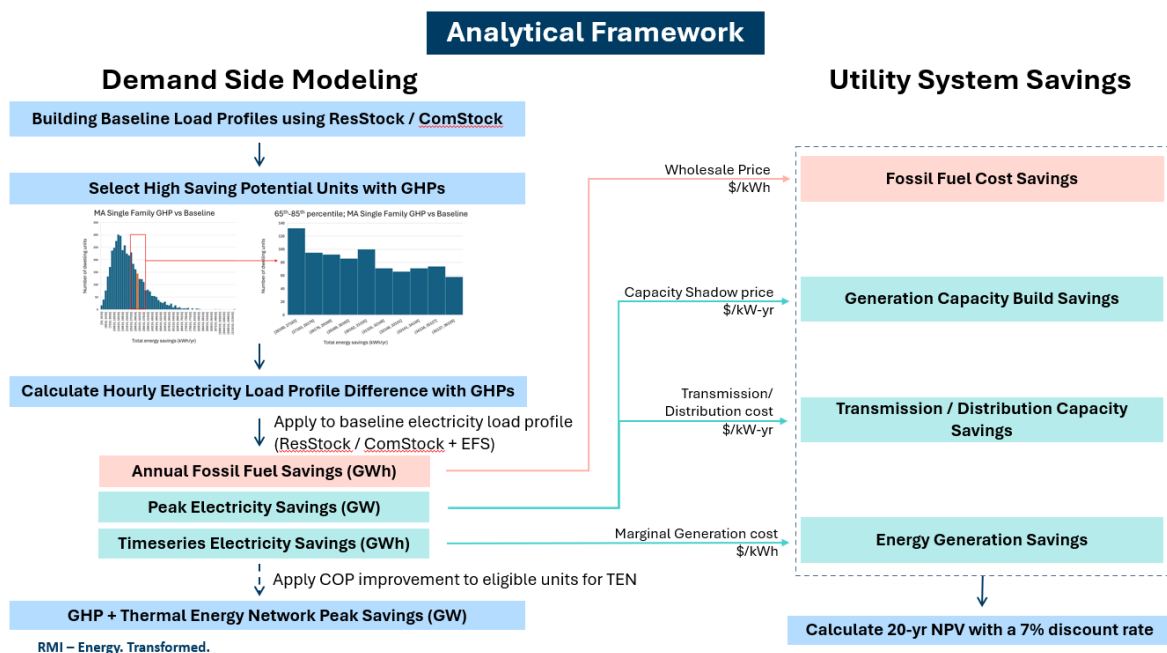


Exhibit 1 illustrates the overall analytical framework used in this study. The analysis first modeled peak demand and energy savings from GHPs at various adoption levels. These demand-side impacts were then translated into utility system savings from reductions in generation capacity build needs, transmission and distribution capacity expansion, energy generation, and wholesale fossil fuel costs associated with heating.

2. Demand-Side Modeling

To estimate the energy and peak demand savings from GHPs, hourly electricity load profiles for GHP upgrades were generated and compared against baseline load profiles for both the Today (2025) and Electrified Future (2040) timeframes.

Baseline hourly electricity load profiles across the residential, commercial, transportation, and industrial sectors were sourced from the 2024 Annual Decarbonization Perspective (ADP 2024) Central Scenario,¹ using 2024 load profiles for the Today timeframe and projected 2040 load profiles for the Electrified Future timeframe.

The following methodology was used to develop hourly GHP electricity savings profiles for residential buildings in Massachusetts and Pennsylvania and commercial buildings in Texas.

GHP upgrade load profiles

1. Obtain GHP upgrade results

Hourly electricity load profiles and annual energy savings associated with GHP upgrades were obtained from National Laboratories of the Rockies' (NLR) ResStock and ComStock datasets.

For the residential analysis in Massachusetts and Pennsylvania, the [Energy Star Geothermal Heat Pump](#) measure from the ResStock 2024.2 dataset was used.² This measure has a rated heating coefficient of performance (COP) of 4 and cooling energy efficiency ratio of 20.5. To align with ResStock's modeled eligibility criteria for this measure, filters were applied to include dwelling units with ducted HVAC systems and no shared HVAC equipment. Additional filters were applied to represent typical occupied homes under realistic operating conditions, including occupied dwelling units, a heating setpoint of 65°F, a cooling setpoint above 80°F, the presence of a cooling system, and a 100% cooled floor area.

For the commercial analysis in Texas, the [Packaged Water-to-Air Geothermal Heat Pumps](#) measure with an average cooling COP of 6.7 and average heating COP of 3.84 from the ComStock 2024 dataset was used. This upgrade represents one of the most common commercial GHP system configurations, utilizing packaged water-to-air heat pumps.

2. Calculate GHP energy savings

For the Today (2025) timeframe, hourly energy savings were calculated as the difference between the baseline building and the GHP upgrade scenario.

For the Electrified Future (2040) timeframe, buildings were assumed to be largely electrified; therefore, hourly energy savings were calculated relative to the business-as-usual (BAU)

electrification technology — the [Cold Climate Air Source Heat Pump with Electric Backup](#) upgrade in ResStock for residential buildings and [Heat Pump Rooftop Unit](#) (HP RTU) upgrades in ComStock for commercial buildings.

3. Select representative models

The distribution of annual GHP energy savings was analyzed to identify representative building models. Buildings with negative modeled savings or statistical outliers were excluded. High-savings buildings, defined as those near the 75th percentile of the savings distribution, were selected to represent achievable GHP performance across the penetration scenarios evaluated in this study.

4. Scale hourly electricity savings

Hourly electricity savings from the representative building models were normalized and scaled according to each adoption scenario. For Massachusetts and Pennsylvania, savings were normalized on a per-dwelling-unit basis and scaled according to the number of applicable dwelling units. For Texas, savings were normalized on a per-square-foot basis and scaled according to the applicable commercial floor area.

5. Develop statewide GHP load profiles

The scaled hourly electricity savings profiles were applied to the corresponding ADP baseline load profiles to generate statewide hourly electricity load profiles under each GHP adoption scenario.

Peak electricity demand reductions and annual electricity savings were then calculated by comparing the GHP adoption load profiles against the corresponding baseline load profiles. These demand-side results served as the primary inputs to the utility system savings analysis.

Hotel and warehouse GHP upgrade load profiles

A simplified approach was used to estimate GHP impacts for hotel and warehouse buildings in the Very High adoption scenario by scaling results from the office and retail analysis under the assumption that load shapes are broadly similar.

1. Hourly heating and cooling loads for office and retail buildings were estimated using average hourly energy savings, baseline HVAC annual average heating and cooling COPs, and GHP heating and cooling COPs. The ratio of annual heating to cooling demand was used as a proxy to separate hourly total savings into heating and cooling savings. All HVAC loads from mid-May through September were assumed to represent cooling only, reflecting the cooling-dominant climate in TX.
2. Hotel and warehouse hourly heating and cooling loads were then estimated by scaling the office and retail results using the ratio of annual heating and cooling demand for each building type. These adjusted loads, combined with annual average baseline HVAC and GHP heating and cooling COPs for hotel and warehouse buildings, were used to calculate hourly energy savings for hotels and warehouses.
3. The resulting hourly savings for 20% of hotel and warehouse buildings were combined with savings from 50% of office and retail buildings and integrated into the baseline and

electrified baseline load profiles from ADP to produce the total electricity load profiles for the Very High adoption scenario.

This approach assumes that hotel and warehouse load shapes are similar to those of office and retail buildings. However, this assumption may not fully reflect actual operating conditions, as hotel loads may more closely resemble residential load patterns — aligning more closely with system peak hours — while warehouse loads may exhibit flatter load profiles. As a result, this approach may underestimate potential peak demand savings.

Thermal energy networks

Modeling thermal energy networks (TENs) is substantially more complex than modeling individual GHP systems because system performance depends on the diversity and interaction of connected building loads. Rather than developing a detailed TEN model, this analysis uses a simplified methodology to estimate the incremental peak demand reduction resulting from the higher system COP achieved by balancing heating and cooling loads for Massachusetts' Electrified Future High Adoption scenario.

The proportion of buildings appropriate for TEN deployment remains uncertain. For this analysis, TEN deployment was evaluated only in medium-density, mixed-use districts, which were assumed to have greater peak savings potential. ResStock, which incorporates data from the American Community Survey, was used to identify dwelling units located in the "metro area, principal city," "metro area, not/partially in principal city," and "not/partially in metro area" location categories. For this analysis, all multifamily dwelling units and 50% of single-family dwelling units located in the "metro area, not/partially in principal city" category were assumed to represent medium-density mixed-use districts. Based on these assumptions, within the High Adoption Scenario, approximately 40% of the single-family homes and 68% of the multifamily homes receiving GHP upgrades were assumed to be deployed as TENs.

Given the uncertainty surrounding achievable TEN performance, two COP assumptions were evaluated. A winter heating COP of 8.9 was based on the Colorado Mesa University TEN analysis, where diverse heating and cooling loads across the campus improve winter system performance.³ Because this value may represent the upper end of expected performance, a more conservative COP of 5 was also evaluated based on values commonly reported in the literature.⁴ A weighted-average heating COP across buildings receiving stand-alone GHPs and TENs was then calculated. Based on the modeled heating load, the improvement in heating COP was used to estimate the additional peak demand reduction attributable to TEN deployment.

3. Utility System Savings

To estimate utility system savings, electricity system cost savings and avoided wholesale fossil fuel costs associated with GHP adoption were quantified using the methodology described below. Annualized values were converted to a 20-year net present value (NPV) using a 7% discount rate, consistent with the assumed lifetime of GHP systems.

Electricity system savings

The following electricity system cost components were quantified based on the peak demand reductions and hourly electricity savings developed through the demand-side modeling analysis.

- 1. Generation capacity savings** were calculated based on peak demand reductions, which reduces the amount of new generation capacity required. Two cost assumptions were evaluated:
 - **Low estimate:** State-specific annual capacity shadow prices (\$/MW firm-year) from the [NLR Cambium 2024](#) High Demand Growth Scenario, converted to a 20-year NPV. Shadow prices were only available at five-year intervals, so linear interpolation was used for intermediate years. These values are derived using a marginal least-cost methodology from NLR's ReEDS capacity expansion model, which allows for delayed retirements, increased transmission, or the cost of new entry for new generation. Notably, these estimates were developed before the recent data center boom.
 - **High estimate:** A combustion turbine (CT) capital cost of \$1,500/kW, based on GridLab's [Gas Turbine Cost Report](#), assuming all new peak demand would otherwise be met by gas CTs. Although the report estimates that recently constructed CT projects can cost up to \$2,000/kW, the more conservative \$1,500/kW estimate, representing the average cost of the plants evaluated in the study, was used for this analysis.
- 2. Energy generation savings** are the savings that result from requiring less generation to meet the estimated hourly demand. Hourly electricity savings from the demand-side modeling analysis were multiplied by hourly marginal generation costs (\$/MWh) from the NLR Cambium 2024 dataset to estimate annual generation savings. MWh savings were assumed to remain constant each year in the 20-year NPV calculation.
- 3. Transmission and distribution (T&D) capacity savings** are the savings that result from lowered capacity, which reduces the T&D infrastructure needed to deliver power. Cost assumptions were informed by the [DER Cost-Effectiveness Avoided Cost Calculator Integrated Calculation Model](#), [The Value of, and Compensation for, Distributed Energy Resources in Illinois](#), and discussions with distribution system experts at RMI. Distribution costs were assumed to be \$106/kW-year, while transmission costs were assumed to be \$80/kW-year, with annual savings converted to a 20-year NPV.

The three components were summed to estimate total electricity system cost savings.

Fossil fuel savings

Fossil fuel savings were only quantified for the Today timeframe. By the Electrified Future timeframe, buildings were assumed to be largely electrified, and reliable projections of wholesale fossil fuel prices are not available; therefore, fossil fuel savings were not estimated for 2040.

Fossil fuel cost savings were calculated by multiplying annual fossil fuel savings estimated from ResStock and ComStock by state-specific wholesale and citygate fuel prices for natural gas, propane, and heating oil (using 2024 state specific data). Wholesale and citygate prices were used

to reflect avoided utility fuel costs rather than retail customer energy bills. A 4% methane leakage rate was assumed.⁵

The following data sources were used:

- **Natural gas prices:** [EIA Natural Gas Citygate Prices](#)
- **Propane and heating oil prices:** [EIA Wholesale Weekly Heating Oil and Propane Prices](#)
- **Natural gas heat rate:** [EPA AP-42, Compilation of Air Pollutant Emissions Factors from Stationary Sources – External Combustion Sources](#)
- **Propane heat rate:** [DOE Alternative Fuels Data Center Fuel Properties Comparison](#)
- **Fuel oil heat rate:** [EIA British Therma Units](#)

Fossil fuel cost savings were added to electricity system savings to estimate total utility system savings for the Today timeframe.

4. Bill Savings

The following describes how electricity and fossil fuel bill savings associated with GHP adoption were quantified to estimate total customer bill savings. Annual values were converted to a 20-year NPV using a 7% discount rate. This analysis assumes that large changes in utility demand profiles would not significantly impact the volumetric retail electricity or fossil fuel rates charged to residential and commercial customers.

- **Electricity bill savings** were calculated by converting total electricity savings into per-unit savings for residential buildings and per-square-foot savings for commercial buildings, then multiplying those savings by state-average residential or commercial retail electricity rates from the [EIA State Energy Profiles](#). Savings were scaled according to the applicable dwelling units or commercial floor area under each GHP adoption scenario.
- **Fossil fuel bill savings** were obtained directly from the ResStock and ComStock datasets, which use state-average retail utility rates for natural gas, propane, and heating oil. Savings were normalized using the output metrics from ResStock and ComStock and scaled according to the applicable dwelling units or commercial floor area under each GHP adoption scenario.

5. GHP Incremental Cost

To estimate the investment required to achieve the quantified utility system savings, the incremental cost of a GHP system relative to the expected BAU replacement system was estimated using the methodology described below. For the Today (2025) timeframe, the BAU replacement system was assumed to be a gas furnace plus central air conditioner (central AC) for residential buildings and a natural gas rooftop unit (NG RTU) for commercial buildings. For the Electrified Future (2040) timeframe, the BAU replacement system was assumed to be an air-source heat pump (ASHP) for residential buildings and an HP RTU for commercial buildings.

Incremental GHP costs were calculated as the difference between the total installed costs of the GHP and BAU systems. HVAC system capacity (tons) for each adoption scenario was estimated

using the NLR ResStock and ComStock datasets (Massachusetts and Pennsylvania analyses use reported heating capacity, and Texas analysis uses reported cooling capacity), while state-specific installed cost assumptions for both GHP and BAU systems were obtained on a \$/ton basis. Total installed system costs for each scenario were then calculated by multiplying the estimated HVAC capacity by the corresponding \$/ton cost assumptions.

For Massachusetts and Pennsylvania, electrical panel upgrade costs were also included in the incremental cost calculation for the Electrified Future (2040) timeframe to account for panel upgrades that may be triggered by the installation of ASHPs. Because it is difficult to determine which individual homes would require panel upgrades, this analysis assumed that a panel upgrade would be required whenever the combined amperage of the ASHP and electric backup heating exceeded 60 amps. The percentage of homes requiring panel upgrades was estimated from the representative ResStock dwelling units and scaled across each adoption scenario. GHPs are modeled and sized without electric resistance backup, so panel upgrades were not assumed for GHP installations.

GHP system costs were obtained using the following state-specific installed cost assumptions:

- **Massachusetts:** Residential GHP installed costs were obtained from the [Massachusetts Heat Pump Incremental Cost Research Memo](#) and adjusted from 2023 to 2025 dollars using the [US Bureau of Labor Statistics CPI Inflation Calculator](#).
- **Pennsylvania:** Residential GHP installed costs were derived by adjusting Massachusetts GHP costs using RSMeans-based labor and material cost indices from the [Heat Pumps in the Northeast and Mid-Atlantic: Costs and Market Trends](#) report, then adjusted from 2023 to 2025 dollars.
- **Texas:** Commercial GHP installed costs were based on cost information provided by industry partners from real-world low-enthalpy geothermal projects in commercial buildings, as standardized cost datasets for these systems are limited.

BAU System Costs were obtained using the following state-specific installed cost assumptions:

- **Massachusetts:** Residential natural gas furnace plus central AC (Today) and ASHP (Electrified Future) installed costs were obtained from the [Massachusetts Heat Pump Incremental Cost Research Memo](#) and adjusted from 2023 to 2025. Electrical panel upgrade costs were based on [Rewiring America estimates](#) using an average installed cost of \$3,000 per panel upgrade.
- **Pennsylvania:** Residential natural gas furnace plus central AC (Today) and ASHP (Electrified Future) installed costs were derived by adjusting Massachusetts costs using the same RSMeans methodology described above, then adjusted from 2023 to 2025 dollars. The same electrical panel upgrade cost from Massachusetts was used.
- **Texas:** Commercial NG RTU and HP RTU installed costs were obtained from TRC Companies' [2025 Nonresidential Alterations: Reach Code Study](#), with HP RTU costs also informed by RMI's [Economics of Electrifying Buildings](#) series. Costs were adjusted from California to Texas using the RSMeans City Cost Index and from 2023 to 2025 dollars.

The state-specific cost assumptions are summarized in Exhibit 2.

Exhibit 2: Average Cost Data (\$/ton)

State	GHP	ASHP	HP RTU	Gas Furnace	Central AC	Gas RTU
Pennsylvania (residential)	\$14,930	\$7,730	-	\$2,040	\$5,040	-
Massachusetts (residential)	\$15,430	\$7,990	-	\$2,100	\$5,210	-
Texas (commercial)	\$6,250	-	\$1,780	-	-	\$1,480

6. Emissions Savings

Fossil fuel emission savings were calculated by applying fuel-specific emission factors from [ResStock 2024.2 Dataset](#) shown in Exhibit 3 to annual reductions in gas, propane, and fuel oil consumption based on the existing fuel types represented in the ResStock and ComStock models used for the analysis.

Exhibit 1: On-Site Fossil Fuel Emission Factors

Fuel Type	Emission Factor (lb./MMBtu)
Natural Gas	147.3
Propane	177.8
Fuel Oil	195.9

Electricity emission savings were calculated using 20-year levelized annual long-run marginal emission rates (LRMER) from the Cambium 22 LRMER States Workbook.⁶ The 95% Decarbonization by 2050 scenario was used for Massachusetts and Pennsylvania, while the Mid-Case scenario was used for Texas. The electricity emission factors used in the analysis are summarized in Exhibit 4.

Exhibit 2: Electricity Emission Factors by States

State	Scenario	Emission Factors (kg CO ₂ e/MWh)	
		2025	2040
PA	95% Decarb by 2050	228.9	70.8
MA	95% Decarb by 2050	198.0	71.8
TX	Mid-case	111.2	89.6

7. Endnotes

¹ Jones, R.A., Haley, B., et al., Annual Decarbonization Perspective: Carbon Neutral Pathways for the United States 2024. Evolved Energy Research, 2024.

² White, P. R., et al., *ResStock 2024.2 Dataset*. National Renewable Energy Laboratory. NREL/TP-5500-89600, 2024, <https://doi.org/10.2172/2340765>.

³ “Evaluating a Community Ground Source Heat Pump System at Colorado Mesa University,” Xcel Energy, 2022.

⁴ *Geothermal Networks: 2019 Feasibility Study*, HEET, and Buro Happold Engineering, 2019 (revised 2023).

⁵ Howarth, R. W., "Methane Emissions from Fossil Fuels: Exploring Recent Changes in Greenhouse-Gas Reporting Requirements for the State of New York," *Journal of Integrative Environmental Sciences* 17 (sup1): 69–81, 2020, <https://doi.org/10.1080/1943815X.2020.1789666>.

⁶ Gagnon, Pieter; Brady Cowiestoll, and Marty Schwarz, Marty, *Long-run Marginal Emission Rates for Electricity - Workbooks for 2022 Cambium Data*, National Laboratory of the Rockies, 2023, <https://data.nlr.gov/submissions/206>.