End-Use Savings Shapes Measure Documentation:

Boiler Replacement with Air-Source Heat Pump Boiler and Natural Gas Boiler Backup

Korbaga Woldekidan

National Renewable Energy Laboratory

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Technical Report
NREL/TP-5500-87536
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List of Acronyms

ASHP	air-source heat pump
CBECS	Commercial Buildings Energy Consumption Survey
COP	coefficient of performance
DHL	design heating load
DOAS	dedicated outdoor air system
EIR	energy efficiency ratio
HDT	heating design temperature
HVAC	heating, ventilating, and air conditioning
LRMER	Long-Run Marginal Emissions Rate
OAT	outdoor air temperature
PLR	part load ratio
PSZ-AC	packaged single zone air conditioner
PVAV	packaged variable air volume
VAV	variable air volume

Executive Summary

Building on the successfully completed efforts to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models over the past three years, the objective of this work is to produce national data sets that will enable analysts working for federal, state, utility, city, and manufacturer stakeholders to answer a wide range of analysis questions.

The goal of this work is to develop load shapes for energy efficiency, electrification, and demand flexibility end-use (electricity, gas, propane, or fuel oil) that cover most of the high-impact, market-ready (or near market-ready) measures. "Measures" refers to energy efficiency variables 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, electrification, or demand flexibility 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 timestep.

ComStock is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual sub hourly energy consumption of the commercial building stock across the United States. The baseline model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology and results of the baseline model are discussed in the final technical report of the End-Use Load Profiles project.

This document focuses on a single end-use savings shape measure—replacing a natural gas-fired boiler with an air-source heat pump boiler. When the outdoor air temperature is below the cutoff temperature of the heat pump boiler, a natural gas boiler is used as a backup. Application of this measure helps to quantify the decarbonization as well as the potential energy savings from the replacement.

This measure is applicable to 33% of the U.S. commercial building stock modeled in ComStock, and the following key observations were made:

- 7.5% total site energy savings (345 TBtu)
- 61.8% heating natural gas savings (512 TBtu)
- 83.2% increase in heating electricity (164.4 TBtu).

Acknowledgments

The author would like to acknowledge the valuable guidance and input provided by Shanti Pless, Eric Bonnema, and the NREL ComStock team, particularly Andrew Parker and Christopher CaraDonna.

The author would also like to thank Bart Ransom from Colmac for providing heat pump performance data.

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1 Boiler Replacement with Air-Source Heat Pump Boiler and Gas Boiler Backup

1.1 Accessing Results

This documentation covers the "Replace Boiler with Air-Source Heat Pump Boiler" upgrade methodology and briefly discusses key results. Results can be accessed on the ComStock™ data lake at "end-use-load-profiles-for-us-building-stock" or via the Data Viewer at comstock.nrel.gov.

1.2 Measure Summary

Measure Title	Replace Boiler with Air-Source Heat Pump Boiler (replace_boiler_with_heatpump)
Measure Definition	This measure replaces a natural gas boiler used for space heating with an air-source heat pump. The air-source heat pump will be the primary source of heat, and the natural gas boiler will be used as a backup.
Applicability	Buildings that use natural gas boilers for space heating and reheating after dehumidification during cooling operations.
Not Applicable	Buildings that do not use natural gas boilers for space heating, such as those with furnaces, electric heaters, or district heat sources. Boilers used for domestic hot water heating will not be replaced in this measure.
Release	2023 Release 1

2 Technology Summary

Air-source heat pump (ASHP) boilers are one of several technologies under consideration for boiler electrification. This technology uses electricity to move heat from the ambient air and transfer it at a higher temperature for space-heating applications. As shown in Figure 1, ASHP boilers function as "refrigeration in reverse" and are usually two to three times more efficient than electric resistance boilers. Because the surrounding air serves as a heat source, the performance of ASHPs depends on the internal energy (related to its temperature) of the outdoor air. With current technology, heat pump capacity and performance generally decrease at lower outdoor temperatures. Heat pump equipment is often controlled to stop operation below a specified outdoor air temperature, often called the cutoff temperature or compressor lockout temperature. The specific value may vary by equipment type and manufacturer, and sometimes the user may specify a value within a limit. Backup boilers are used for operation below the shutdown temperature. Like the performance and capacity maintenance of heat pump, shutdown temperature of the compressor may improve with technology development.

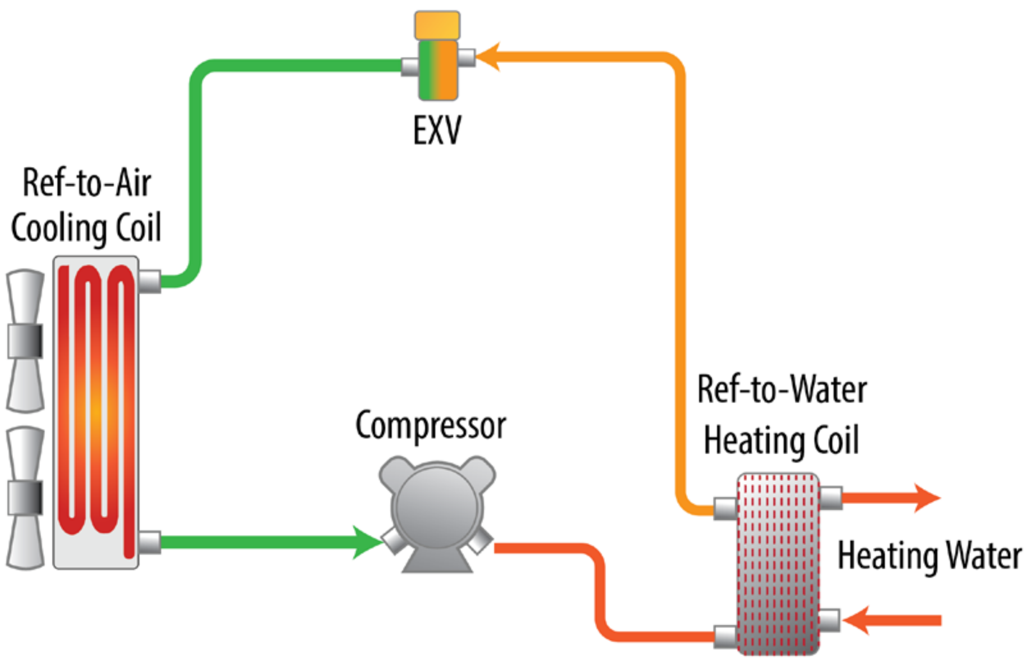


Figure 1. ASHP boiler operation

All figures by NREL unless otherwise noted.

3 ComStock Baseline Approach

The current version of the boilers in ComStock are gas-fired, noncondensing boilers. Their efficiencies were determined using the U.S. Department of Energy's reference building templates and capacities. The values are summarized in Table 1 [3]. Three different cubic performance curves based on the part load ratio (PLR) are used to adjust the boiler efficiency, as shown in Table 2. Figure 2 shows the variations of boiler efficiency multipliers with PLR based on the three performance curves, a graphical representation of the curves' output. All ComStock boilers have a heating set point of 180°F and can modulate flow based on heating load.

Table 1. Boiler Efficiency and Performance Curve Assignment

Template	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Minimum Annual Fuel Utilization Efficiency (AFUE)	Minimum Thermal Efficiency (%)	Minimum Com-bustion Efficiency (%)	Efficiency Function of Part Load Ratio (EFFFPLR)	Notes
Pre-1980	-	299,999		0.73		Boiler Constant Efficiency Curve	From DOE Reference Buildings
Pre-1980	300,000	no max		0.74			
Pre-1980	250,000,000	249,999,999		0.76			
1980-2004	-	299,999	0.8				From 90.1-1989
1980-2004	300,000	249,999,999			0.8		
90.1-2004	-	299,999	0.8			Boiler with No Minimum Turndown	From 90.1-2004
90.1-2004	300,000	249,999,999		0.75			
90.1-2004	250,000,000	no max			0.8		
90.1-2007	-	299,999	0.8				From 90.1-2007
90.1-2007	300,000	249,999,999		0.8			
90.1-2007	250,000,000	no max			0.82		
90.1-2010	-	299,999	0.8				From 90.1-2010
90.1-2010	300,000	249,999,999		0.8			
90.1-2010	250,000,000	no max			0.82		
90.1-2013	-	299,999	0.82				From 90.1-2013 From 90.1-2016
90.1-2013	300,000	999,999		0.8			
90.1-2013	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2013	250,000,000	no max			0.82		
90.1-2016	-	299,999	0.82			Boiler with No Minimum Turndown	
90.1-2016	300,000	999,999		0.8			
90.1-2016	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2016	250,000,000	no max			0.82		
90.1-2019	-	299,999	0.84			Boiler with No Minimum Turndown	From 90.1-2019
90.1-2019	300,000	999,999		0.8			
90.1-2019	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2019	250,000,000	no max			0.82		

Table 2. Boiler Performance Curves

Name	Form	Dependent Variable	Independent Variable 1	coeff_1	coeff_2	coeff_3	coeff_4	Notes
Boiler Constant Efficiency Curve	Cubic	Efficiency Multiplier	Part Load Ratio	1	0	0	0	From DOE Reference Building
Boiler with Minimum Turndown				0.7791	1.4745	-2.5795	1.3467	From Regression of Prototype Building EMS
Boiler with No Minimum Turndown				0.7463	1.3196	-2.2154	1.1674	From Regression of Prototype Building EMS

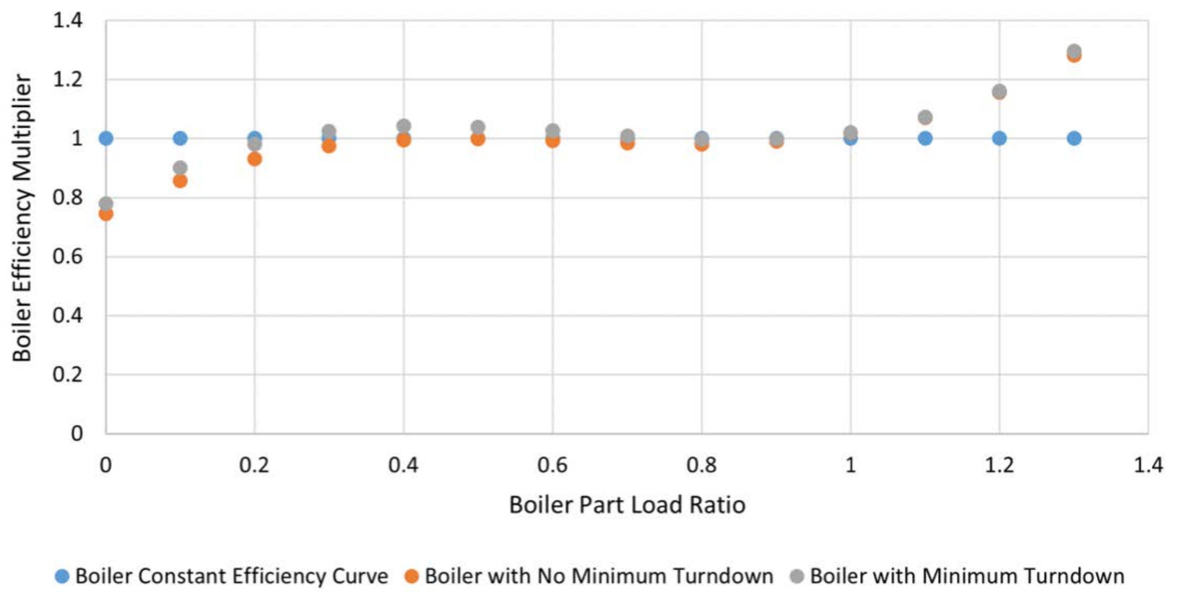


Figure 2. Boiler performance curves

4 Modeling Approach

According to the Commercial Buildings Energy Consumption Survey (CBECS), natural gas used by boilers and furnaces accounts for 73% of space-heating energy consumption in U.S. commercial buildings [4]. This measure replaces natural gas boilers used for HVAC applications with heat pump boilers. The results of the simulations could be used to estimate the carbon reduction and energy impacts from electrifying these boilers.

The measure provides several options for replacing natural gas boilers. Table 1 summarizes the measure inputs and their default values used in the simulation run.

Table 3. Measure Input Summary

Measure Inputs	Description	Default Value	Units
Keep_setpoint	Option to keep the original hot water set point.	False	True/False
hw_setpoint	New hot water set point if user chooses to change the original value.	140	˚F
autosize_hc	Option to auto-size heating coils when a user provides a new hot water set point.	True	True/False
Sizing_method	Option for sizing the heat pump. The two options are sizing based on "percentage of peak load" and on "outdoor air temperature."	Outdoor air temperature	-
hp_sizing_temp	Outdoor air temperature on which to base ASHP sizing if user chooses the sizing method as "outdoor air temperature."	17	˚F
hp_sizing_per	Percentage of the peak heating load on which to base the sizing if user chooses the sizing method as "percentage of peak load."	70	%
hp_des_cap	Maximum design heat pump heating capacity per unit. If the model requires a higher capacity, multiple units will be added in the loop.	40	kW

Measure Inputs	Description	Default Value	Units
bu_type	Two options for backup heater: keeping the existing boiler or adding an electric resistance boiler.	Natural gas boiler	-
hpwh_cutoff_Temp	Cutoff temperature for the heat pump boiler.	−5	˚F
hpwh_Design_OAT	Design outdoor air temperature for the heat pump boiler.	47	˚F
COP	Design coefficient of performance (COP) at the design outdoor air temperature.	2.85	-

4.1 Applicability

Figure 3 shows the distribution of heating types among ComStock buildings. This measure applies to buildings heated by a gas boiler, which represents 33% of the ComStock baseline total floor area. The orange bar in the figure indicates the percentages for the corresponding buildings. Of the buildings with boilers, this measure is applicable to 94% of the buildings, with the remainder being boilers used for supplemental heating for heat pump applications.

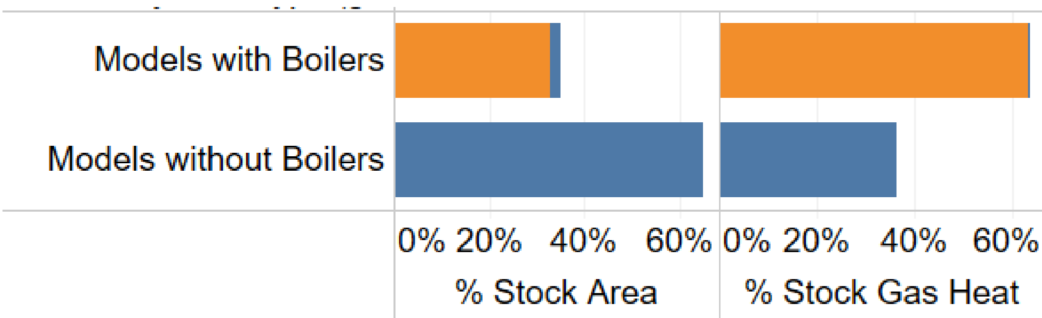


Figure 3. Measure applicability

This measure is applicable to the ComStock OpenStudio® models with the following heating, ventilating, and air conditioning (HVAC) system types (Table 4):

Table 4. Applicable HVAC System Types

	Applicable HVAC System Types
1	Dedicated outdoor air system (DOAS) with fan coil air-cooled chiller and boiler
2	DOAS with fan coil chiller and boiler
3	DOAS with fan coil district chilled water and boiler
4	DOAS with water-source heat pump cooling tower and boiler
5	Packaged single zone air conditioner (PSZ-AC) with gas boiler
6	Packaged variable air volume (PVAV) with gas boiler
7	PVAV with gas heat with electric reheat
8	Variable air volume air-cooled chiller with gas boiler reheat
9	Variable air volume chiller with gas boiler reheat
10	Variable air volume district chilled water with gas boiler reheat

4.2 ASHP Sizing

Heat pump sizing is a critical step to consider when retrofitting a boiler with an ASHP boiler. The sizing process requires consideration of several factors, such as: [2]

- Design heating water supply temperature
- Design heating outdoor temperature
- Equipment costs
- Operating costs

- Electrical infrastructure cost to support the higher peak demand from switching to an electric heating source from a gas-fired heating source
- Carbon emission reduction.

Optimal sizing is a balance of the above factors and should be based on the priorities of the building owner. Most commercially available ASHP boilers are relatively small and require cascading for higher capacities. Aside from requiring more space for installation, cascading provides flexibility, improves efficiency at part load operation, and increases system redundancy and resiliency.

Two ASHP sizing methods are offered for this measure. In the first method the ASHP is sized based on the percentage of the peak load, with the ASHP target capacity determined as a percentage of the design heating load (DHL) on the heating load line as shown in Figure 4. The heat load line is defined as the line connecting the zero-heating load at the heat enabling outdoor temperature, assumed to be 60°F, and the DHL at the winter heating design day outdoor temperature, while the DHL is assumed to be the same as the heating capacity of the existing boiler.

In the second method, sizing is based on a specified outdoor temperature. In this method, the target ASHP capacity is determined by selecting a point on a heating load line that corresponds to the outdoor air temperature.

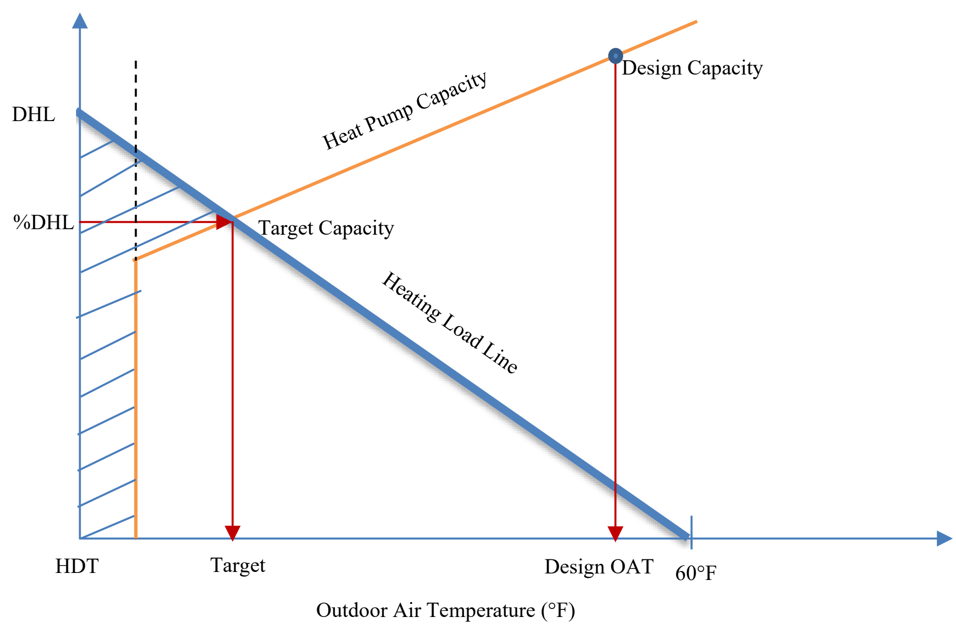


Figure 4. Heat pump sizing approach

Note that with current technology, heat pump capacity changes with outdoor temperature. Most heat pump manufacturers specify the heat pump rated capacity at a certain condition, usually at an outdoor temperature of 47°F. Thus, the target capacity estimated by either method must be converted to the required capacity at the design conditions. To estimate the required rated capacity of the heat pump at the design outdoor temperature, we used a performance curve called $CapFT$ [9] that captures the variation of a heat pump's capacity with outdoor air temperature and hot water set point. The target capacity at the design outdoor air temperature (Target Capacity @ Design OAT) is estimated as:

$$Target\ Capacity\ @\ Design\ OAT = \frac{Target\ Capcity}{CapFT\ @\ Target\ OAT}$$

$$CapFT@Target\ OAT = a + b * T_{cond_{out}} + c * T_{cond_{out}}^2 + d * Tareget\ OAT + e * Target\ OAT^2 + f * T_{cond_{out}} * Target\ OAT$$

where a, b, c, d, e, and f are *CapFT* performance curve coefficients, and $Tcond_{out}$ is the hot water temperature at the condenser outlet of the heat pump (which is equivalent to the hot water heating set point).

For more detail information on sizing, readers are encouraged to refer the measure documentation for boiler replacement with air source heat pump boiler and electric boiler backup from Commercial EUSS 2023 Release 1.

4.3 Modeling ASHP Boilers in OpenStudio

A heating model with a plant loop heat pump energy efficiency ratio (EIR) is used to model the ASHP boiler. However, the current version of this model does not support flow modulation and requires the full design flow from the plant [9]. Consequently, it cannot be directly integrated into a hot water loop with a variable speed pump. To overcome this limitation and provide the necessary separation between the hot water loop and the heat pump, we added a heat pump loop to the existing building model (refer to Figure 5). The heat pump loop consists of a heat pump on the supply side and a fluid-to-fluid heat exchanger on the demand side. This heat exchanger, connected in series with the existing boiler, serves as the primary heating source, while the boiler handles the remaining load.

To deal with multiple heat pumps in the heat pump loop, we implemented a "sequentialLoad" control scheme, where the heat pumps are activated in sequence until the heating load is met. To maintain the system efficiency despite the presence of a heat exchanger, we assumed an "ideal" heat exchanger, considering its effectiveness to be 1. Additionally, we utilized an "UncontrolledOn" control scheme for the heat exchanger, which allows it to operate whenever there is nonzero flow in the main hot water loop.

Furthermore, it is worth noting that this heat pump model lacks a cutoff temperature. To address this, we incorporated an "AvailabilityManagerLowTemperatureTurnOff" to the heat pump loop. This function turns off the loop when the outdoor air temperature drops below the specified cutoff temperature.

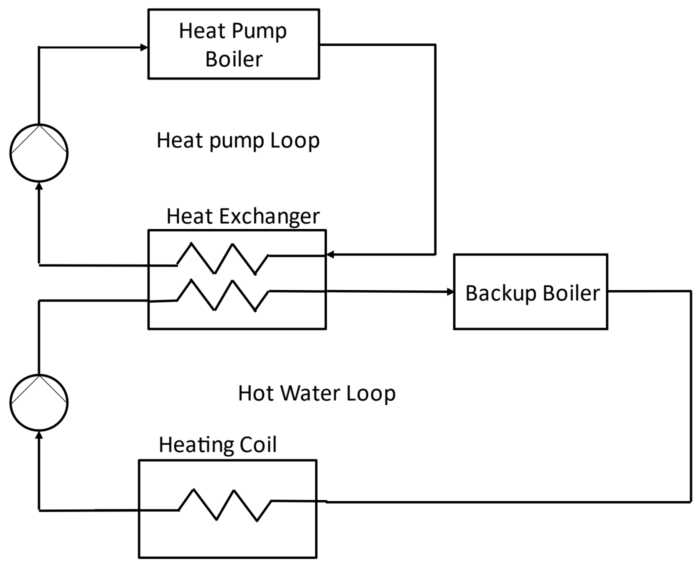


Figure 5. Configuration of heat pump and hot water loops

The plant loop heat pump EIR heating model uses three performance curves—CapFTemp, EIRFTemp, and EIRPLR—to capture the impact of operating conditions on capacity and performance.

CapFTemp modifies the capacity of the heat pump based on the outdoor air and heat pump condenser outlet temperatures:

$$CapFTemp = a_1 + b_1 (T_{cond,out}) + c_1 (T_{cond,out})^2 + d_1 (T_{air,in}) + e_1 (T_{air,in})^2 + f_1 (T_{air,in}) (T_{cond,out})$$

EIRFTemp modifies the EIR, which is the inverse of the coefficient of performance (COP), of the heat pump based on outdoor and heat pump condenser outlet temperatures:

$$EIRFTemp = a_2 + b_2 (T_{cond,out}) + c_2 (T_{cond,out})^2 + d_2 (T_{air,in}) + e_2(T_{air,in})^2 + f_2 (T_{air,in}) (T_{cond,out})$$

EIRPLR modifies the EIR of the heat pump based on the part load ratio (PLR) and captures efficiency loss from compressor cycling:

$$EIRPLR = a_3 + b_3\, PLR + c_3\, PLR^2$$

We used data provided by Colmac [13] to generate the CapFTemp and EIRFTemp performance curves. During the measure development, we were unable to find performance data for EIRPLR. Thus, we assumed a linear variation between EIR and PLR that resulted in a 0% reduction in EIR at 1 PLR and a 25% reduction in EIR when PLR was near zero. More details on the performance curves can be found in Appendix A.

Figure 6 and Figure 7 show how the CAPFT and EIRFT curve output values change with outdoor air temperature and hot water outlet temperature. As shown in Figure 6, the CAPFT value increases with increasing outdoor temperature and condenser outlet temperature. The

EIRFT curve shown in Figure 7 shows a decrease in EIR (improvement in COP) as the outdoor temperature increases and the condenser leaving water temperature decreases.

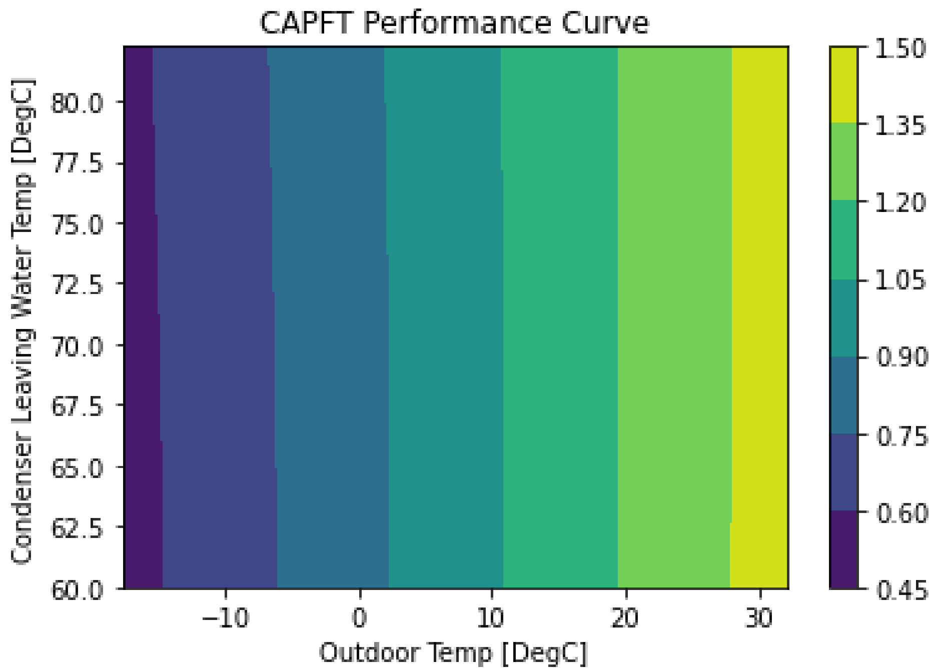


Figure 6. CAPFT performance curve output

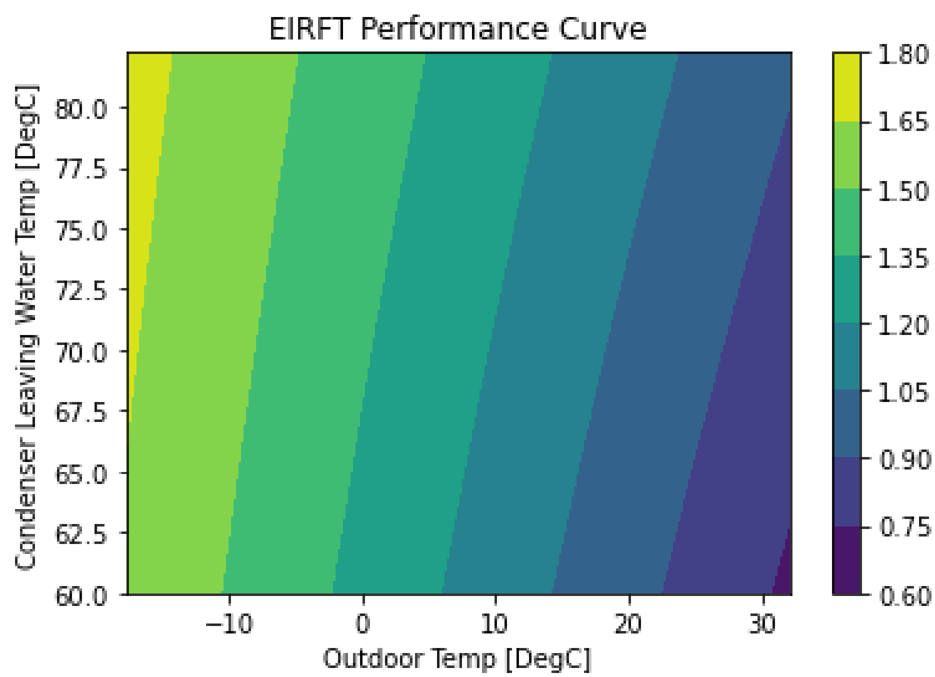


Figure 7. EIRFT performance curve output

4.4 Limitations and Concerns

As mentioned in Section 3, some of the boilers in the baseline ComStock models do not have a minimum load turndown control. This allows for low flow with insignificant heating in the hot water loop. This had a negative impact in the application of this measure, because the measure introduces a heat pump loop that is triggered by a nonzero flow in the hot water loop. The low flow in the hot water loop forces the heat pump to cycle frequently and eventually affects the expected savings from the application of this measure. But this issue affects only a very small fraction of buildings in hot climates and the impact on overall savings is very small. This issue should be addressed in the next version of the ComStock models.

The heat pump object used in this measure—the plant loop EIR heating heat pump—is a constant flow model that requires full design flow from the plant. This model assumption limits the modeling of variable speed heat pumps and results in frequent cycling of the heat pump, leading to inefficiencies in the system. This measure could be updated in the future once the updated version of the heat pump object with a variable speed option is available.

To account for relatively lower hot water supply temperatures of heat pump boilers, the measure provides an option to auto size the heating coils and associated systems. Even if the overall impact is minimal, in some buildings the auto sizing provides a design outdoor air flow rate that is much slower than the baseline cases, resulting in savings in cooling energy consumptions. This is due to differences in how design outdoor airflow rate is calculated and controlled when the baseline model is created, and how the auto sizing re-sizes and controls the ventilation. This issue will be addressed in the future.

5 Output Variables

Table 5 provides a list of the output variables that are calculated in ComStock. These variables are important in terms of understanding the differences between buildings with and without the replace_boiler_by_heatpump measure applied. These output variables can also be used for understanding the economics of the upgrade (e.g., return on investment) when cost information (i.e., material, labor, and maintenance costs for technology implementation) is available.

Table 5. Output Variables Calculated from the Measure Application

Variable Name	Description
Heat pump capacity weighted design COP	COP of the heat pump at the rated design conditions
Heat pump average COP	Average heat pump COP
Heat pump total load	Total heating provided by heat pump
Boiler total load	Total heating provided by boiler
Heat pump total electricity	Total electricity consumption by heat pump
Boiler total electricity	Total electricity consumption by boiler
Heat pump capacity kBtuh	Heat pump capacity
Count heat pumps	Count of heat pumps
Count heat pumps 0–300 kBtuh	Count of heat pumps in the range of 0–300 kBtuh capacity
Count heat pumps 300–2,500 kBtuh	Count of heat pumps in the range of 300–2,500 kBtuh capacity
Count heat pumps 2,500+ kBtuh	Count of heat pumps with more than 2500 kBtuh capacity
Hot water loop total load	Total heating load in the hot water loop
Hot water loop boiler fraction	Fraction of heating load provided by boiler
Hot water loop heat pump fraction	Fraction of heating load provided by heat pump

6 Results

6.1 Single Building Model Example

Table 6 shows a comparison of an end-use energy consumption for a 37,491 square-foot large office building model in Denver, CO, before and after application of the default measure inputs. The two energy end-use categories that are significantly affected by this measure are heating and cooling energy. For the same heating load, the total heating energy consumption drops by ~24% from 532 GJ to 403 GJ. Note that the natural gas consumption for the updated case is the one used by the backup natural gas boiler. Overall, the electric consumption increases by ~5% while natural gas consumption drops by ~48%.

Table 6. End-Use Energy Consumption Comparison

End Use	Baseline		Updated	
	Electricity [GJ]	Natural Gas [GJ]	Electricity [GJ]	Natural Gas [GJ]
Heating	99	433	176	227
Cooling	291	0	296	0
Interior Lighting	551	0	551	0
Exterior Lighting	75	0	75	0
Interior Equipment	380	0	380	0
Exterior Equipment	0	0	0	0
Fans	204	0	204	0
Pumps	59	0	59	0
Heat Rejection	15	0	15	0
Humidification	0	0	0	0
Heat Recovery	0	0	0	0
Water Systems	15	0	15	0
Refrigeration	0	0	0	0
Generators	0	0	0	0
Total End Uses	**1689.09**	**433.03**	**1770.93**	**226.92**

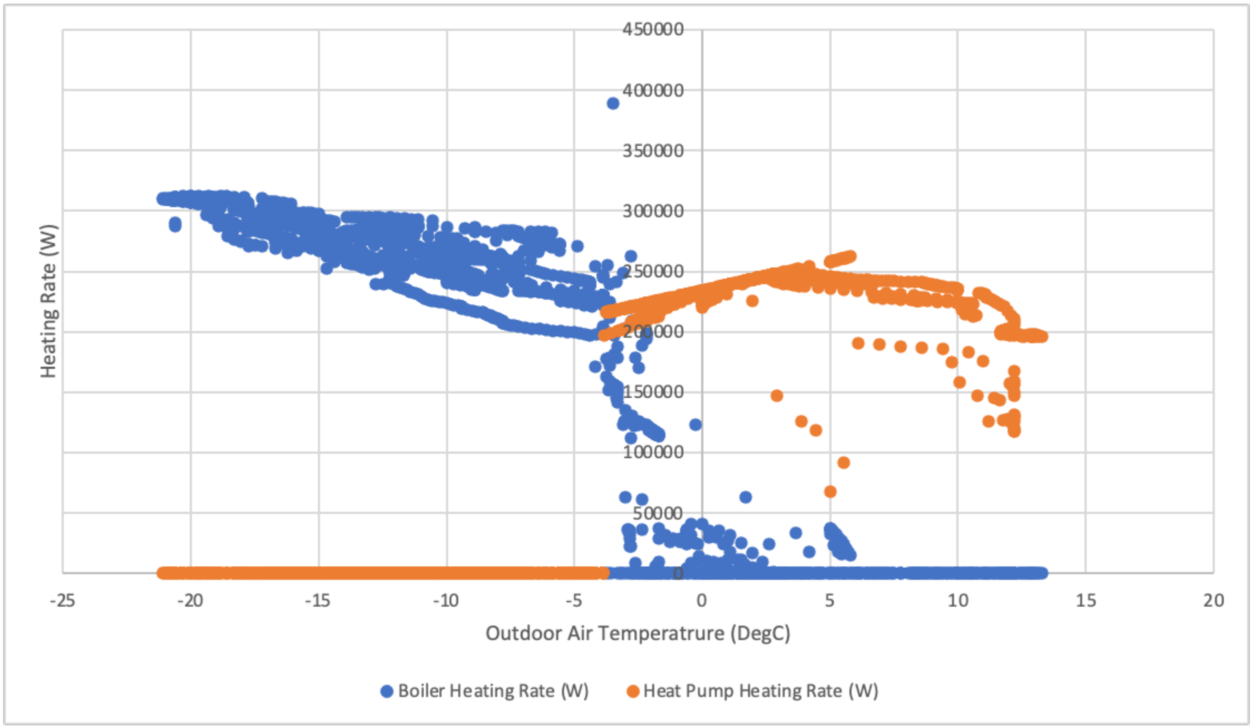


Figure 8. Sequencing between ASHP and boiler

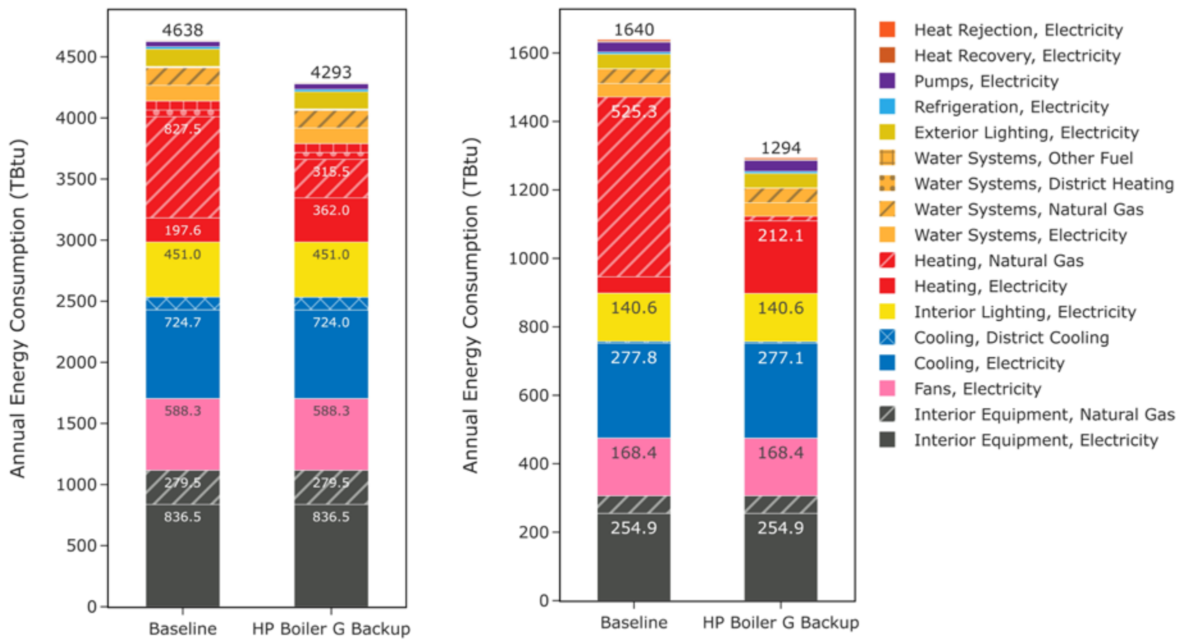
We checked the sequencing between the heat pump and the boiler during low-temperature operation using an example cutoff temperature of 25°F (−4°C). Figure 8 shows the operation pattern. As expected, the heat pump handled most of the load at a higher temperature. The boiler starts supplementing the ASHP as the temperatures drops and takes over all heating when the temperature is below the cutoff temperature.

6.2 Stock Energy Impact

As noted above, this measure is applicable to buildings that use natural gas boilers for HVAC systems, which represents 33% of the floor area of the U.S. commercial building stock modeled in ComStock. The following key observations can be made from application of the measure.

- 7.5% total site energy savings (345 TBtu)
- 41% total natural gas energy savings (512 TBtu)
- 5.3% increase in total electricity (164.4 TBtu)
- 61.8% heating natural gas savings
- 83.2% increase in heating electricity.

As shown in Figure 9, this measure has negligible impact on most end-use categories, with the exception of heating electricity, heating natural gas, and pump electricity. The remaining gas heating in applicable buildings comes from backup heating, and a small subset of non-applicable systems (e.g., boilers that serve condenser water loops).



(a) (b)

Figure 9. End-use energy consumption comparison for (a) ComStock Buildings and (b) applicable buildings

6.3 Stock Peak Impacts

Figure 10 shows the impact of the upgrade on the average daily maximum peak demand per square foot across the ComStock building models. There is no increase in summer, while 0.5% and 5% increases are observed during the shoulder and winter seasons, respectively. This is to be expected, since the heat pump boiler operates mainly during the winter and sometimes during shoulder season. Heat pump peak demand depends on many factors, including climate, cutoff temperature, heat pump capacity, heat pump type (constant speed, variable speed), backup heating type and capacity, unit efficiency, and operating characteristics (e.g., thermostat schedule).

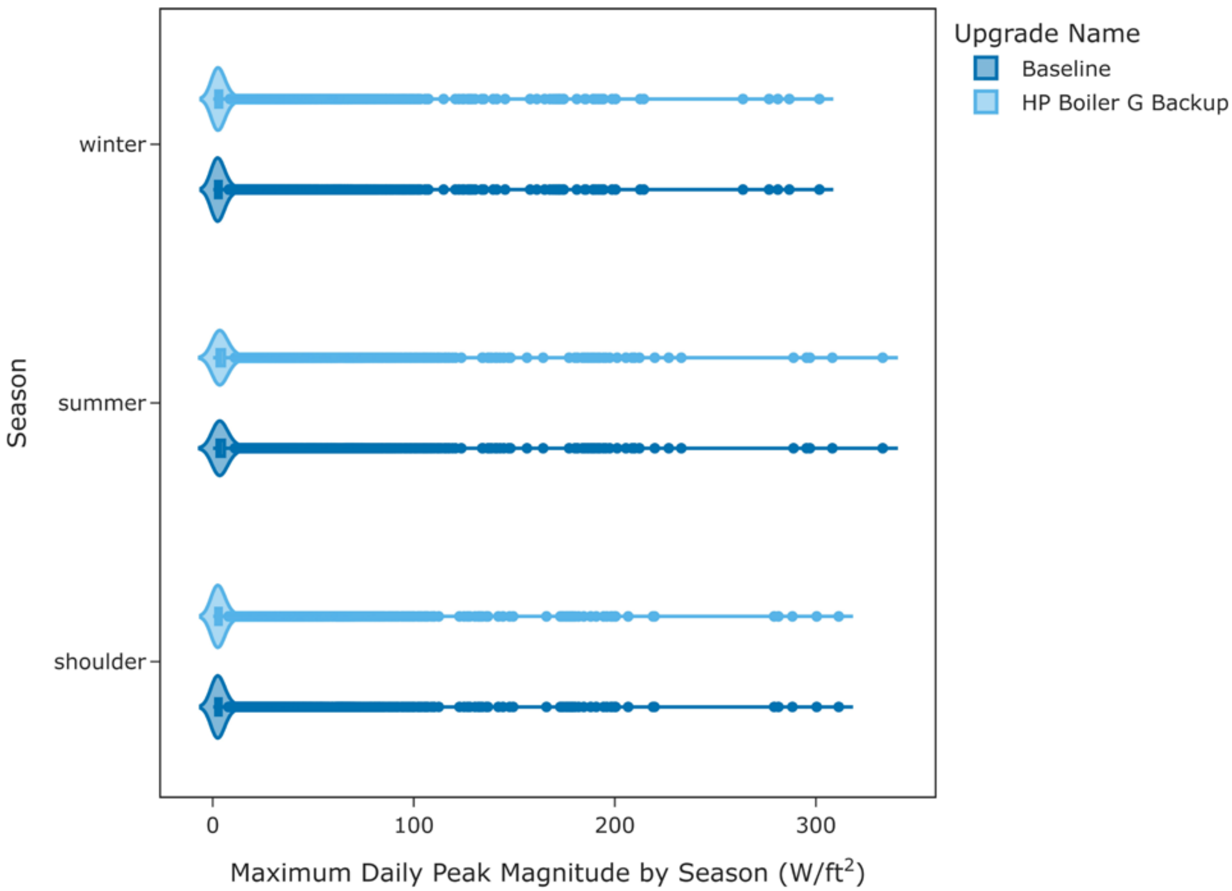


Figure 10. Average daily maximum peak demand comparison

6.4 Measure Impact by HVAC System Type

Figure 11 shows the percent site energy savings by different types of HVAC system. DOAS with water-source heat pump cooling tower with boiler and PVAV with gas heating with electric reheat had the lowest savings. The primary reason for the limited savings for the DOAS with water-source heat pump cooling tower with boiler is that the heat pumps predominantly fulfill the heating load while the boiler solely provides heating for the DOAS units. Also, this measure only replaces the boilers in the hot water loop and doesn't replace supplemental boilers in the condenser loop for heat pump applications. In the case of the PVAV with gas heating and an electric reheat system, the reduced savings are attributed to the presence of electric reheat coils in the VAVs, which provide most of the heating. On the other hand, the VAV systems with boiler reheat show higher savings. This is mainly because the floor areas they serve are relatively large, which makes them well suited for the application of this measure.

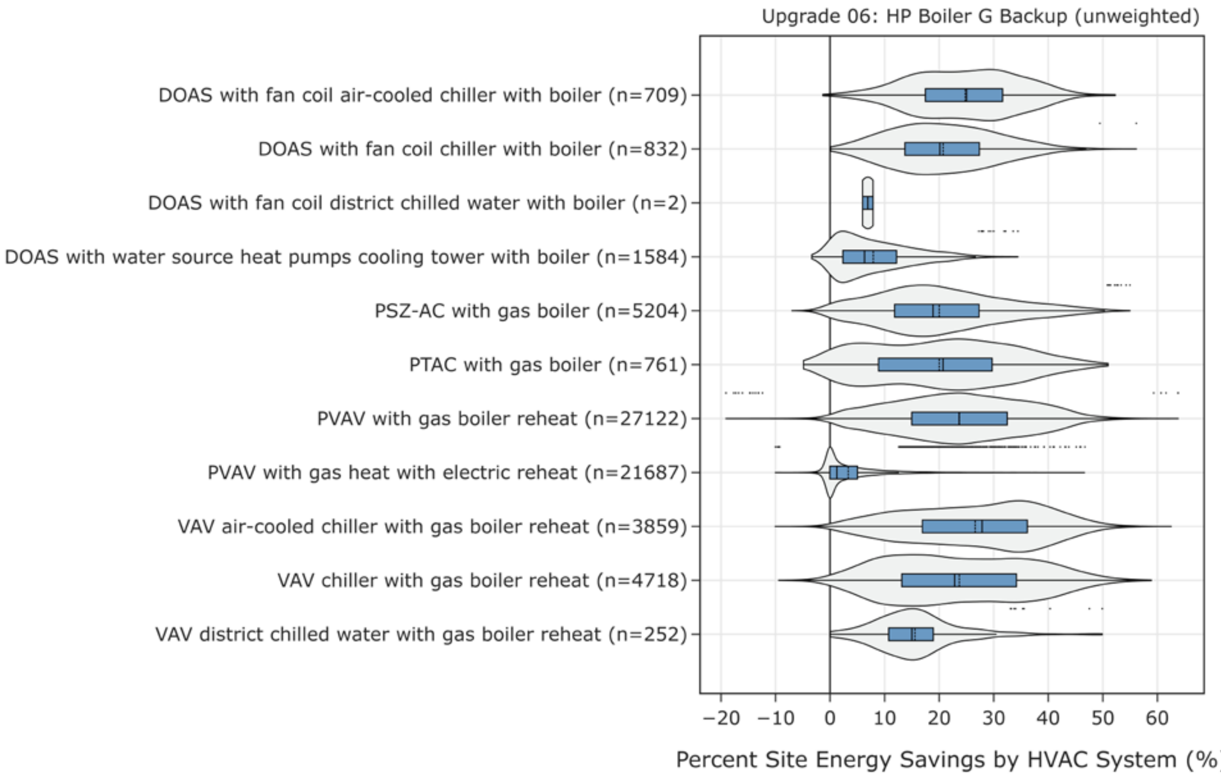


Figure 11. Percent site energy savings by HVAC system type

In each category, there were a few buildings that had negative savings due to their very low heating loads. In the baseline case, these loads were managed by modulating the boiler. However, in the updated case, the low flow in the hot water loop triggered the heat exchanger to request flow in the heat pump loop. However, the heat pump model used only supports a constant flow, which resulted in frequent cycling of the heat pumps, as shown in Figure 12. This resulted in higher energy consumption compared to the baseline. Only a very small fraction of the total buildings demonstrated this behavior, rendering its impact on the overall result to be minimal, and the absolute energy impact was small.

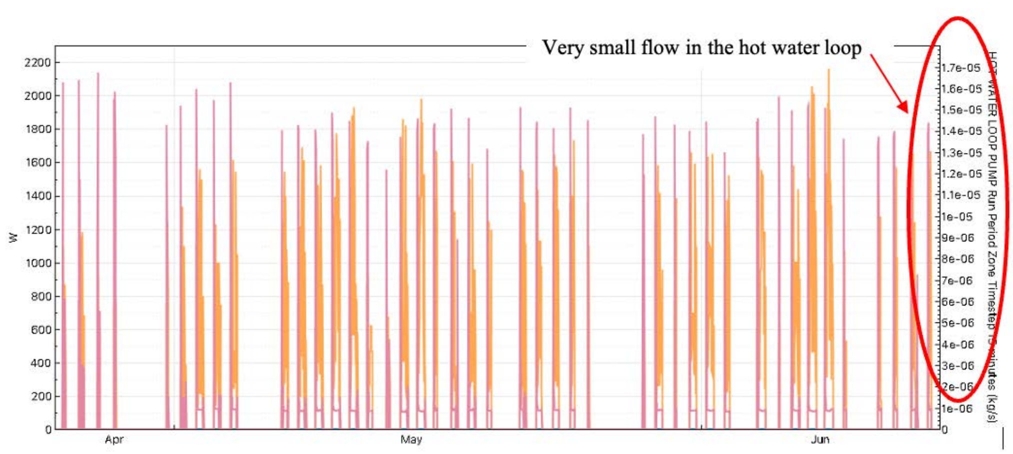


Figure 12. Flow in the hot water loop that triggers heat pump operation

6.5 Measure Impact by End Use

The impact of the measure on end-use energy consumption is shown in Figure 13. As expected, the end uses that are affected most are natural gas heating, pump electricity, and heating electricity. Most of the natural gas consumption (except for backup heating) is replaced with electricity. The increase in electricity consumption due to the heat pump boiler addition is indicated by a negative percentage savings for electricity heating. Electricity consumption for pumps increases due to the addition of a circulation pump in the heat pump loop. A very small subset of buildings exhibited an unexpected natural gas consumption increase and a reduction in pump electricity use. These buildings are buildings in a hot climate using VAVs with electric reheat where most of the heating is handled by the electric reheat coils and the boiler rarely runs. The observed increase in natural gas consumption is not an actual increase, instead it is caused by solution convergence difference. Similarly, the unexpected saving from pump electricity consumption in some buildings is due to presence of significantly low heating load in the hot water loop that is prohibiting the heat exchanger in the loop from activating. This causes both the hot water loop and heat pump loop pumps not to run and resulted in pump energy savings. In these buildings, the electric reheat coils are operating in the absence of a heat source from the hot water loop to maintain the required zone temperature and no increase in unmet hours was observed. The minor changes in the other end uses are due to the change in the hot water set point from 180°F for the baseline to 140°F.

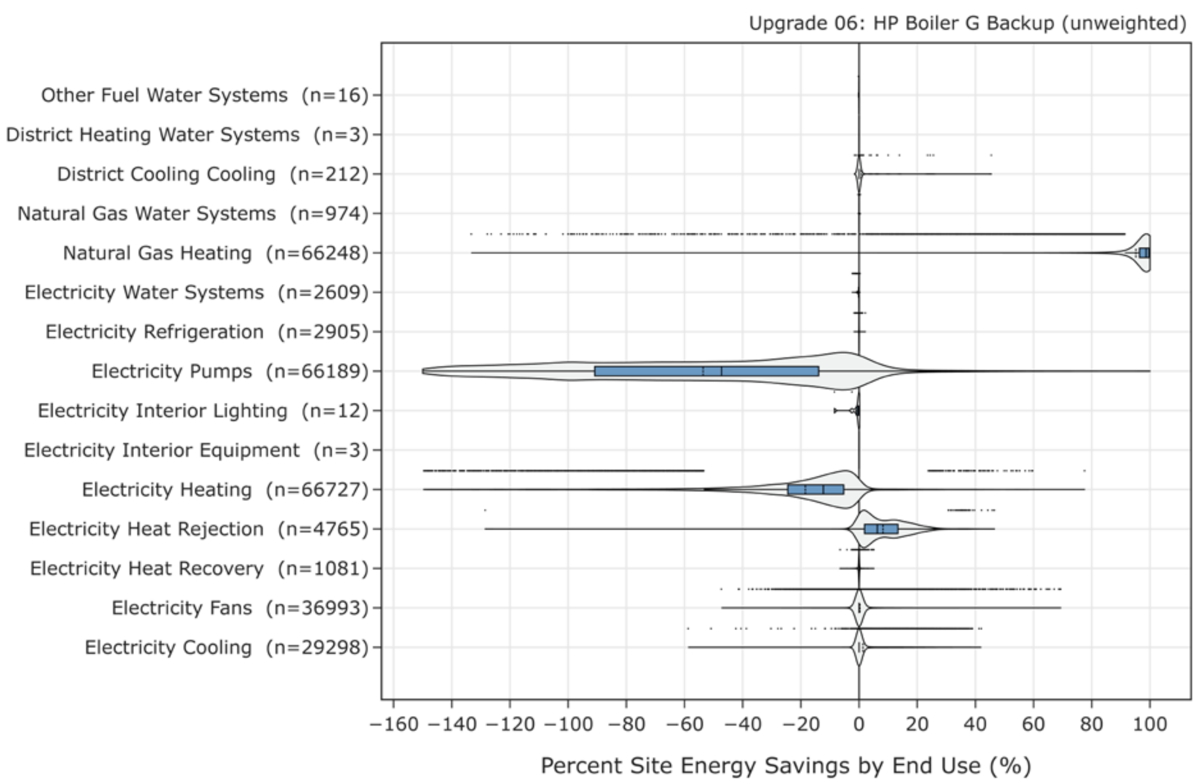


Figure 13. Percent savings by end use

6.6 Measure Impact by Building Type

Figure 14 shows the impact of the measure by building type. Hospitals, primary schools, and secondary schools are the three building types with the highest site energy savings, whereas quick-service restaurants have the lowest. The higher savings in these three buildings are attributed to their HVAC system type as well as their relatively higher heating loads. Only ~1% of ComStock quick-service restaurant buildings use a boiler, which resulting in lower savings from application of this measure. In contrast, 63% of hospitals, primary schools, and secondary schools use a boiler, resulting in the observed higher site energy savings.

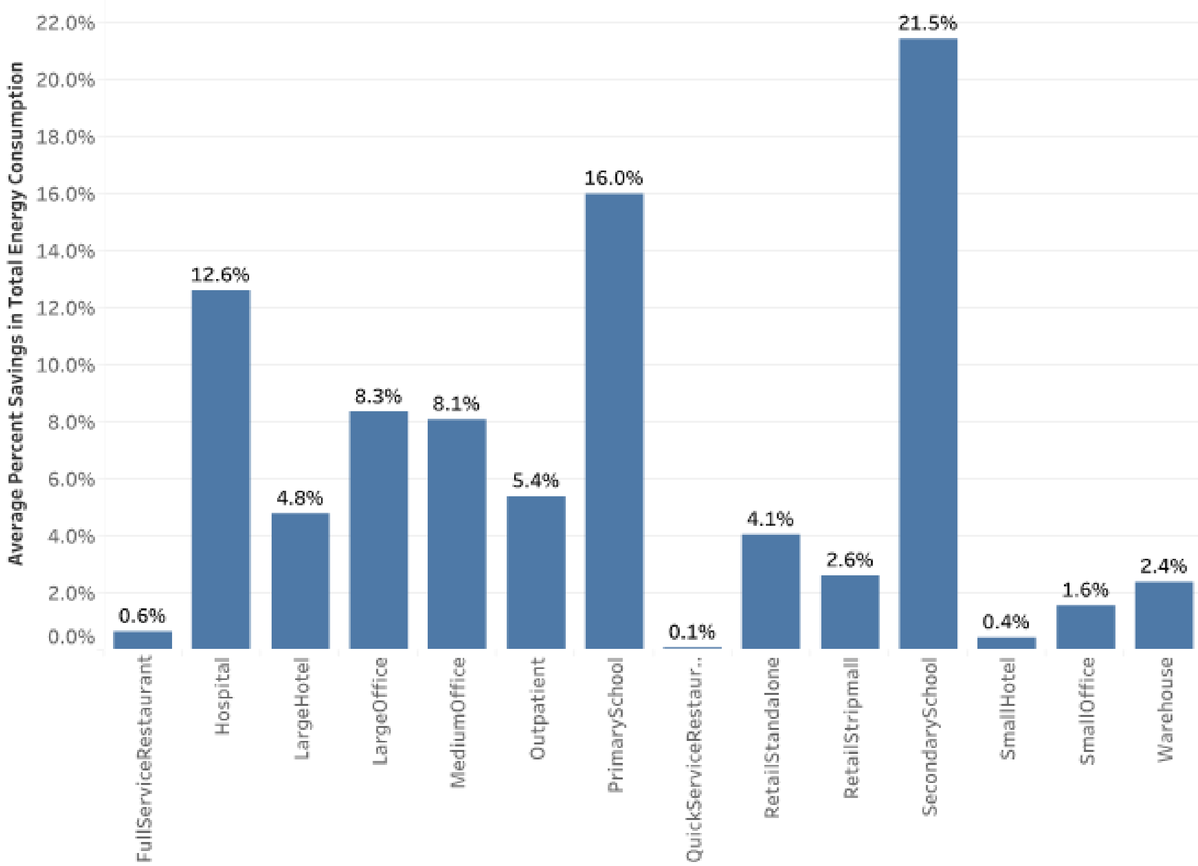


Figure 14. Stock-wide total site energy savings by building type

6.7 Measure Impact by State

Figure 15 and Figure 16 show the average percentage distribution of natural gas and electricity savings across the entire building stock by state. As expected, cold regions showed higher savings in natural gas consumption and higher increases in electricity energy use. The state-level average increase in electricity consumptions is indicated by negative savings. Note that savings are also affected by buildings type distribution and total floor area in each state. Besides the need for more electricity because of the heat pump boilers in the colder regions, the high electricity demand is also in part due to the lower efficiency of the heat pump boilers in these regions. The unexpected electricity saving observed in Florida is due to cooling energy savings in some buildings due to the model auto sizing limitation discussed in Section 4.4. As indicated in Figure

9, no significant stock level cooling electricity energy consumption difference is observed due to the upgrade, confirming only very few buildings exhibited cooling energy savings and the impact is negligible.

Figure 17 shows the COP variations in each state. In general, heat pump boilers operate at a higher efficiency in hot climates than in cold ones.

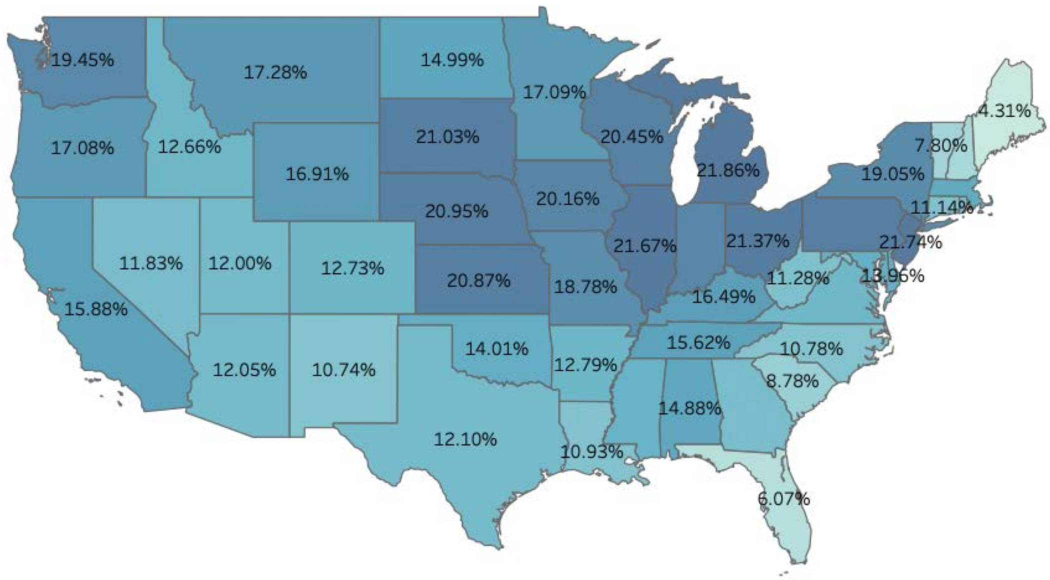


Figure 15. percentage savings in natural gas

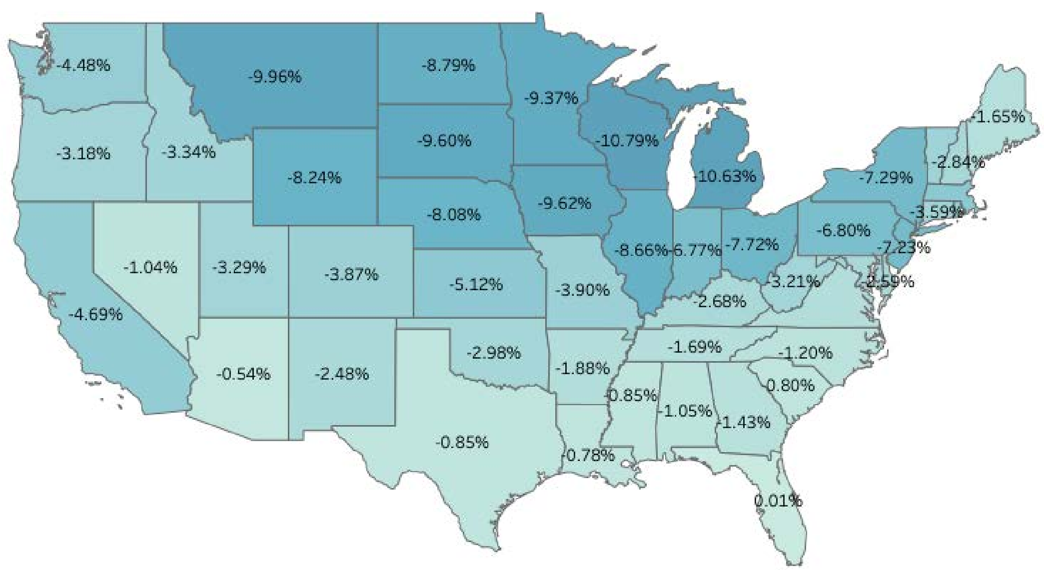


Figure 16. Percentage savings in electricity consumption

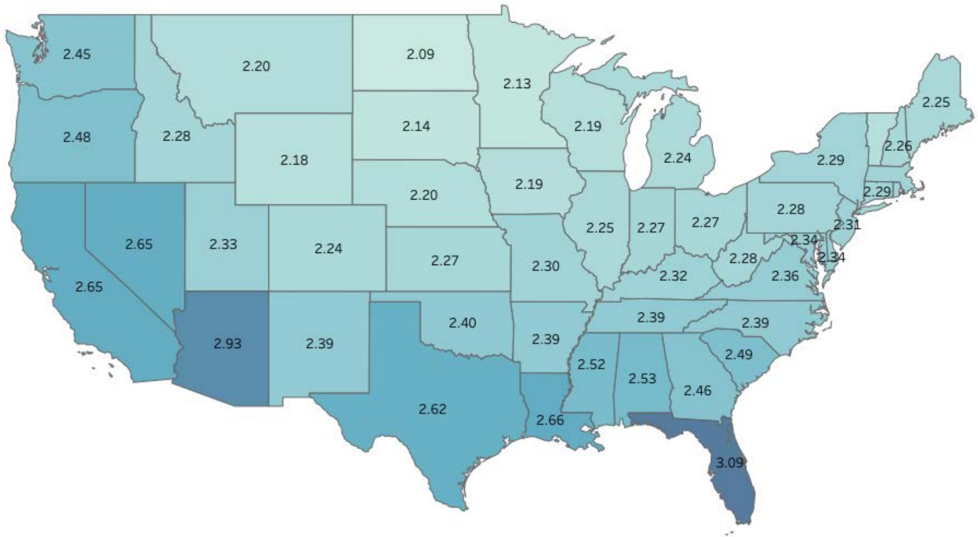


Figure 17. Heat pump average COP

6.8 Measure Impact on Greenhouse Gas Emissions

Figure 18 illustrates the comparison of annual greenhouse gas emissions between the baseline and the upgrade. As expected, emissions from natural gas decreased while emissions from electricity increased. The overall reduction in greenhouse gas emissions depends on the emission source. Three sources of electricity are considered for comparison: Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year, Cambium LRMER Low RE Cost 15-Year, and emission and generation resource integrated database (eGRID). The percentage values in the figure indicate percentage increase or decrease in emissions compared to the baseline. All upgrade scenarios resulted in net emissions avoided in combined emissions from electricity and on-site combustion fuels, with the comparison using LRMER Low RE Cost scenario resulting in the highest net savings of 22.6 MMT (9.2%).

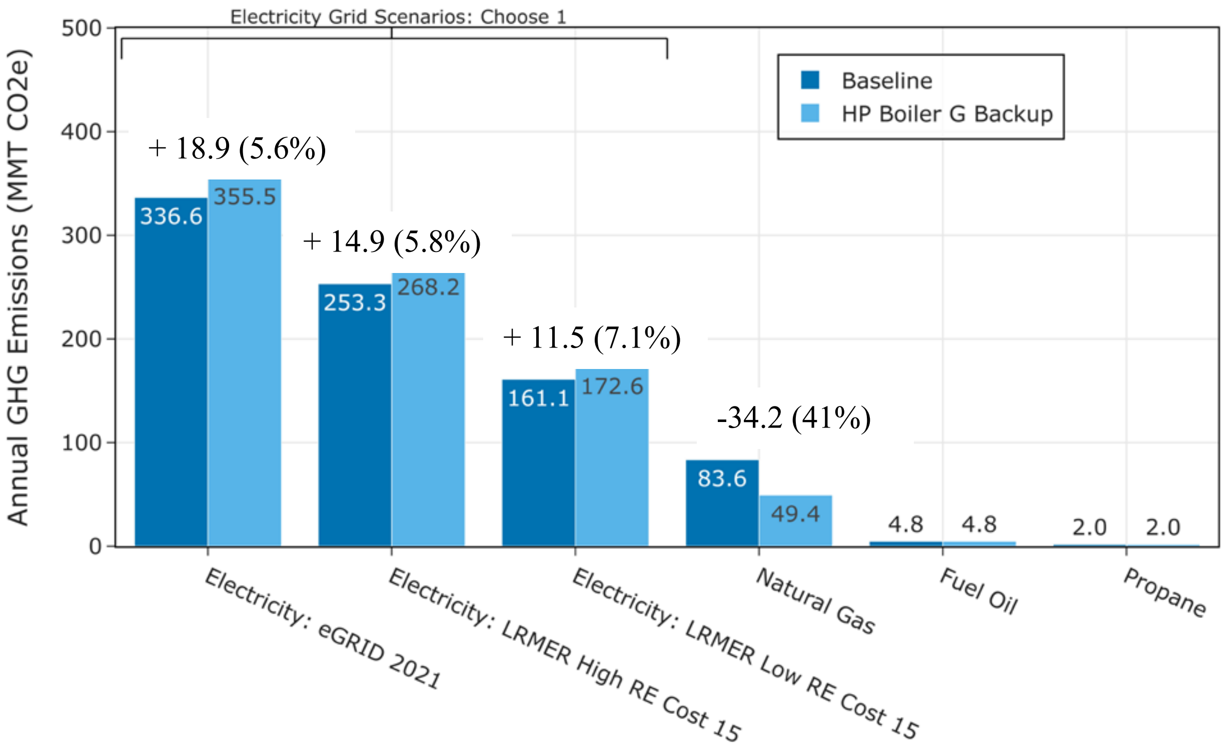


Figure 18. Annual greenhouse gas emission comparison

6.9 Comparison of Measure Upgrade with Gas and Electric Backup

Figure 19 shows a comparison of end-use energy consumption after implementing a measure with gas and electric backup for relevant buildings. As anticipated, the electric heating option completely replaced 100% of the natural gas consumption for heating. For the gas backup case, 97.5% of the natural gas heating was replaced with electricity while the rest was used for backup. Consequently, the measure with electric backup exhibits higher electric consumption than the gas backup option, with the electric backup option consuming 3.5% more.

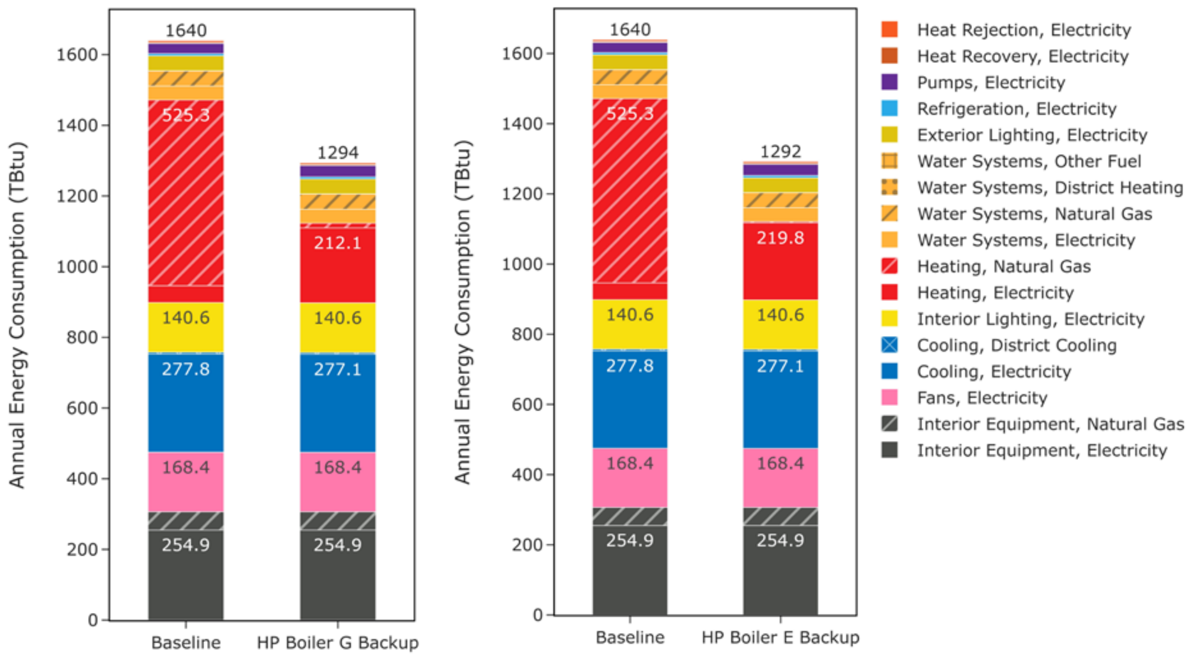


Figure 19. End-use annual energy consumption *comparison for gas and electric backup options*

As illustrated in Figure 20, no significant difference was observed between the gas and electric backup options in terms of their impact on peak demand. However, it can be observed that there is a considerable increase in peak demands compared to the baseline scenarios in subarctic and very cold regions. This is expected because these regions have a higher need for heating, and electrifying the boiler using a heat pump boiler would significantly increase the electricity demand.

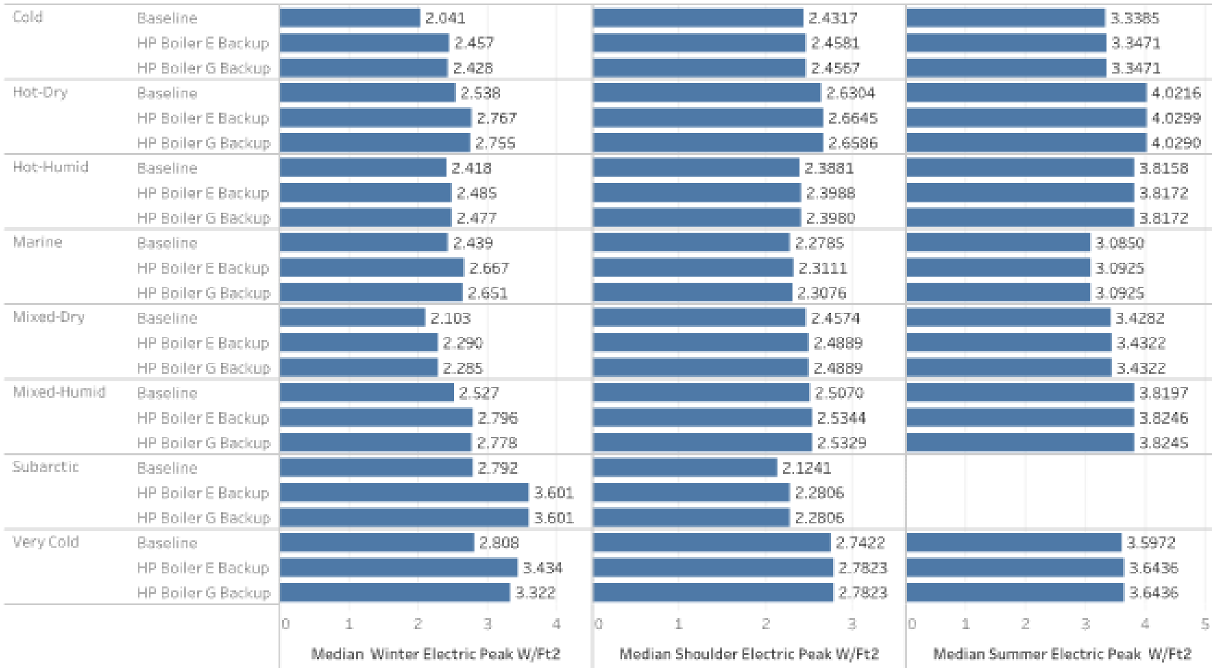


Figure 20. Comparison of impact on peak demand for gas and electric backup options

As with the peak demand observation, no significant difference was found in the net annual emissions savings between the two backup options. Figure 21 illustrates net greenhouse gas emission savings from the electricity grid scenarios and on-site combustion fuels (natural gas, propane, and other fuels). The preferred backup fuel type may vary based on the specific priorities for a project and should collectively consider energy costs, peak demand implications, prevalence of on-site combustion of fossil fuels, and other design constraints.

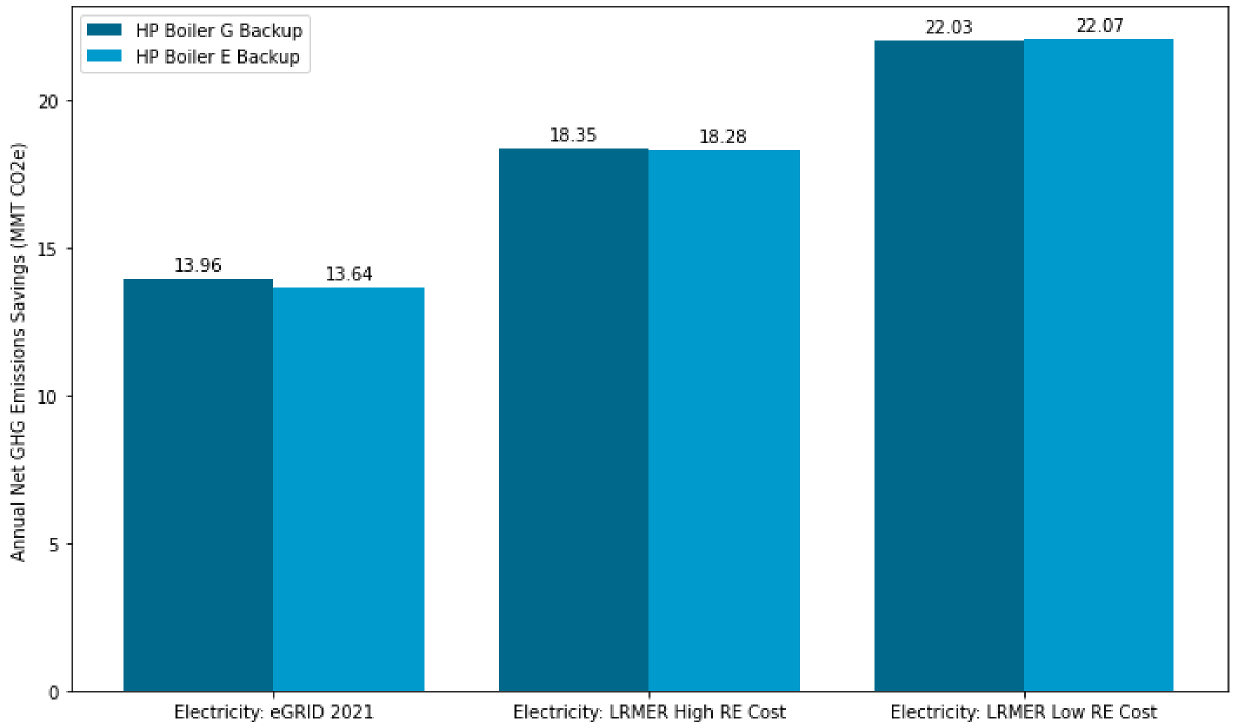


Figure 21. Annual net greenhouse gas (GHG) emission saving comparison between gas and electric backup options

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Appendix A

A.1 Appendix ASHP Boiler Performance Curve Generation

As discussed in Section 4.3, the heat pump model used in this measure has three performance curves for capturing the dependency of the heat pump performance on the operating conditions. Two of the curves, capacity as a function of temperature (CapFTemp) and energy input ratio (EIR) as a function of temperature (EIRFTemp), capture the dependency of heat pump capacity and efficiency on outdoor air temperature and hot water supply temperature. EIR as a function of part load ratio (EIRPLR) captures the dependency of the heat pump efficiency on heat pump loading and cycling.

$$Q_{Available} = Q_{Reference} \times CapFTemp$$

$$P = P_{Reference} * EIRFTemp * EIRPLR$$

$$CapFTemp = a1 + b1\,(T_{cond,out}) + c1\,(T_{cond,out})^2 + d1\,(T_{air,in}) + e1\,(T_{air,in})^2 + f1\,(T_{air,in})\,(T_{cond,out})$$

$$EIRFTemp = a2 + b2\,(T_{cond,out}) + c2(T_{cond,out})^2 + d2\,(T_{air,\,in}) + e2(T_{air,in})^2 + f2\,(T_{air,in})\,(T_{cond,out})$$

$$EIRPLR = a3 + b3\,PLR + C3\,PLR^2$$

Where $Q_{Reference}$ is the design heating capacity of the heat pump, $P_{Reference}$ is the design power demand of the heat pump, $Q_{Available}$ is the adjusted heating capacity, P is the adjusted power demand, $T_{cond,out}$ is the condenser outlet water temperature, $T_{air,in}$ is the ambient air temperature, PLR is heat pump part load ratio, and a1, b1, c1, d1, e1 … c3 are performance curve coefficients that need to be extracted from operational data.

The two temperature-dependent performance curves, CapFTemp and EIRFTemp, were generated using performance data provided by Colmac. It is important to note that the efficiency of the heat pump is influenced not only by the operating temperature conditions but also by factors such as the load on the heat pump and its cycling frequency. During the development of the measurement, we encountered a challenge in obtaining manufacturer data to account for this dependency. As a result, we assumed a linear variation between EIR and PLR. According to this assumption, there is no reduction in efficiency when the PLR is one (indicating full load), and a 25% reduction in efficiency when the PLR is close to zero (indicating low load).

In order to evaluate the accuracy of the Colmac performance data, we compared data from Trane and Mitsubishi. Unfortunately, detailed data for the two units from Trane and Mitsubishi were not available. However, the capacity drop with outdoor air temperature observed in the Colmac unit appeared to be consistent with the data from Trane and Mitsubishi.

The results of the comparison are summarized in Table A-1 and Table A-2. According to the data, the capacity reductions for the Trane and Colmac units were found to be 44% and 50%, respectively, as the temperature decreased from 47°F to 0°F. On the other hand, the Mitsubishi data indicates a 31% capacity reduction as the outdoor air temperature decreases from 45°F to

20°F, while the Colmac unit shows a slightly lower reduction of 25% within the same temperature range.

Table A-1. Capacity Reduction with OAT for Trane and Colmac Units

	Capacity at 50°F (Btu/hr)	Capacity at 0°F (Btu/hr)	% Capacity Reduction From 50°F to 0°F	COP
Colmac [14]	57,600	31,500	**45%**	2.70 @ 50°F
Trane [2]	-	-	**50%**	2.70 @ 47°F

Table A-2. Capacity Reduction Comparison Between Mitsubishi and Colmac Units

	Capacity at 45°F (Btu/hr)	Capacity at 20°F (Btu/hr)	% Capacity Reduction From 50°F to 20°F	COP
Colmac [14]	54,750	42,200	**23%**	2.70 @ 50°F
Mitsubishi [10]	140,400	117,234	**25%**	2.85 @ 45°F

Table A-3 summarizes the performance curve coefficients that are estimated using the Colmac data. The curve outputs for different combinations of condenser water leaving temperature and outdoor air temperature are indicated in Figure A-1 and Figure A-2.

Table A-3. Performance Curve Coefficients

	CAPFT	EIRFT	EIRPLR
a	0.88302749	0.84177647	1.25
b	−0.0016513	0.00648504	−0.25
c	1.44E−05	−8.68E−06	0
d	0.01833385	−0.0273677	-
e	3.6396E−05	0.00018754	-
f	−2.04E−05	0.0001082	-

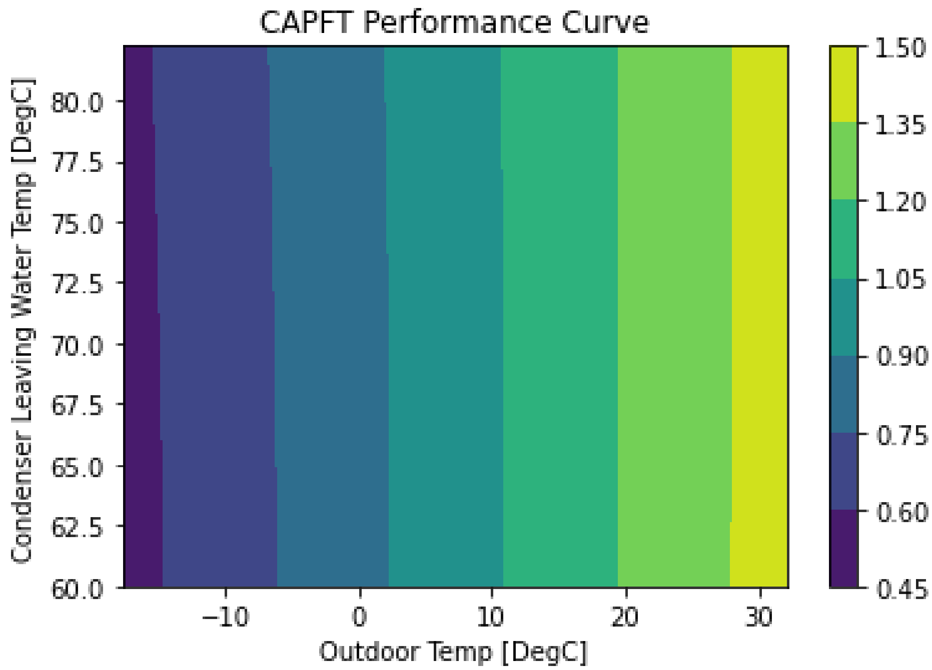

Figure A-1. CAPFT performance curve output

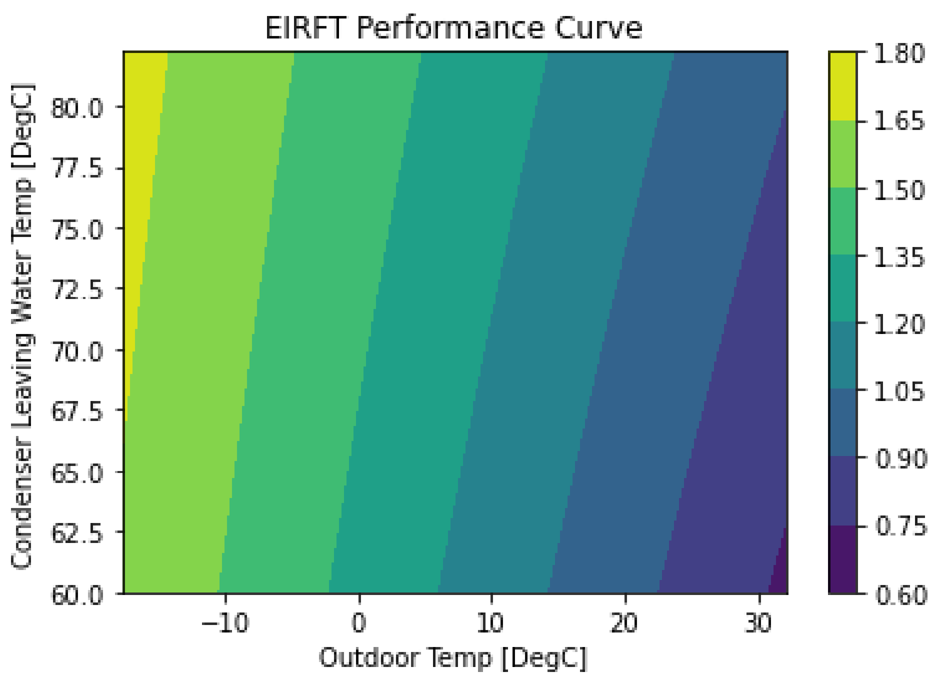

Figure A-2. EIRFT performance curve output

Figure A-3 illustrates the comparison between the actual heating capacity and EIR with the estimated values obtained using the performance curves for various combinations of outdoor air temperature and condenser water leaving temperature (CWLT). The figure demonstrates a satisfactory agreement between the two, providing assurance that we can confidently utilize the performance curves for modeling ASHP boilers.

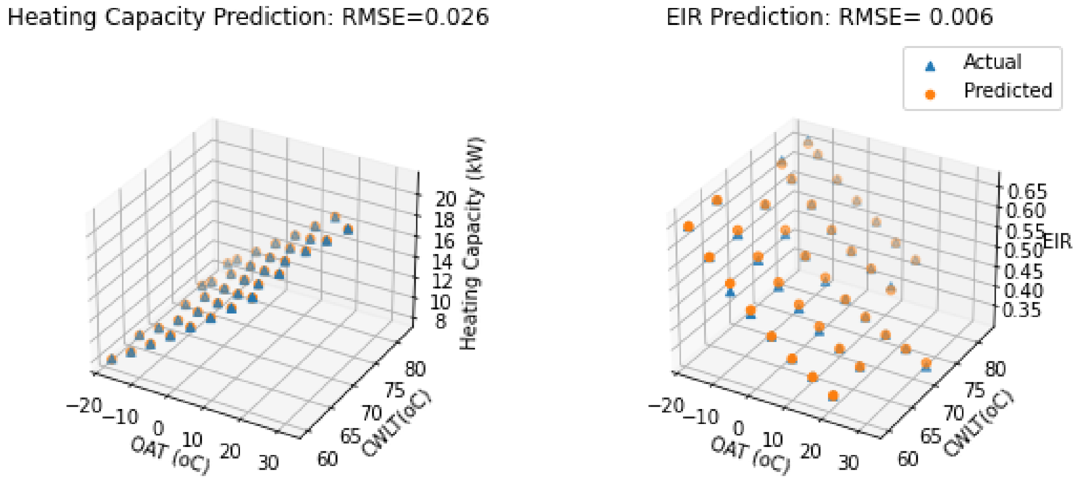

Figure A-3. Comparisons of predicted and actual capacity and EIR