Memorandum

Introduction

To: **Massachusetts Residential Program Administrators**

From: **Daniel Ferrante, Ryan Powanda, and Ken Seiden, Guidehouse**

Date: **September 2, 2022**

Re: **Heat Pump Switchover Temperature Optimization Study Memo**

Guidehouse Inc. (Guidehouse) developed this memorandum to present the results of the Heat Pump Switchover Temperature Optimization study. This study estimates the ideal ambient air temperature under which the heat pump (HP) compressor operation should be locked out to minimize total customer utility costs for space heating for dual-fuel heat pump system installations with fossil fuel backup heat.

In addition to this memorandum, the primary deliverable for this study is an Excel-based Switchover Temperature Optimization Calculator (herein referred to as the calculator). The calculator calculates the optimal switchover temperatures and documents the data sources used to inform inputs and model assumptions. All inputs in the calculator can be easily modified to calculate results for revised scenarios or to adjust assumptions in the future. The tool can be used by the Massachusetts Program Administrators (PAs) to revise program guidance on an ongoing basis in response to changing utility rates, revised program requirements, or the availability of more accurate input data.[1]

This quick-hit study supports program guidance for the Energy Optimization Fuel Displacement heat pump measures offered through the Mass Save programs. These electrification initiatives are in place to encourage customers to reduce reliance on energy and CO_2-intensive fuel oil, propane, natural gas, and electric resistance baseboard heating systems and displace their energy consumption through more efficient heat pump systems.

Two displacement scenarios are possible through the energy optimization program: partial displacement and full displacement. In full displacement applications, the customer installs a heat pump(s) without an integrated controller, and any backup or emergency heating is used only during extreme conditions when supplemental heating capacity is required. For most installations, backup heat is provided by electric resistance or a wood or pellet stove. Customers who receive a rebate for full displacement heat pump installations also sign a verification form signifying that they have either removed or disconnected their pre-existing fuel-fired heating system, and if left installed, will only use it in the case of an emergency (heat pump down time or in extreme weather conditions).

In partial displacement installations, an integrated controller is also installed and used to sequence fossil and heat pump systems based on the outdoor air temperature. This study will focus on partial displacement installations, where the existing fossil fuel system is left in place

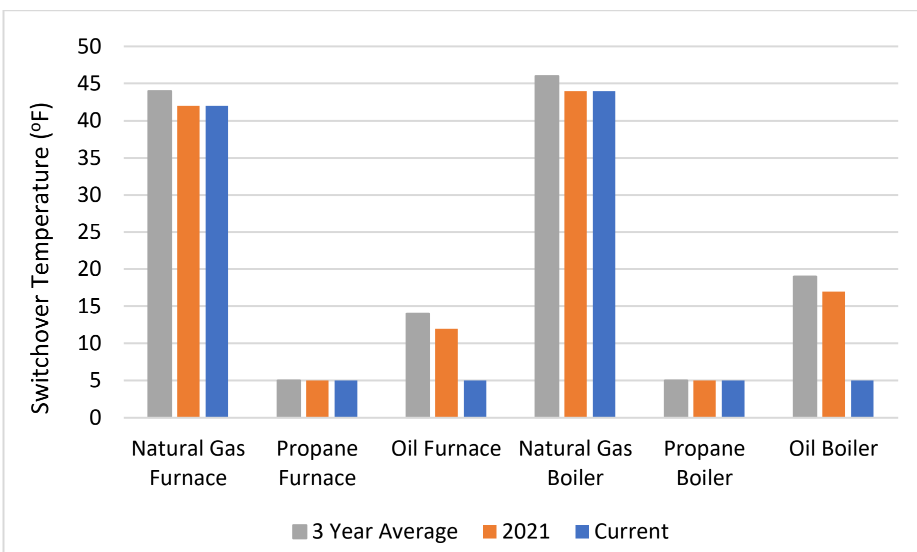
[1] The PAs have asked the team to plan and implement a heat pump metering impact study in late 2022 through 2024, the results of which can be used to update several optimal switchover model assumptions (e.g., performance curves, performance derate factors, typical system efficiencies).

and an integrated controller is used to sequence the HVAC equipment. The integrated controller prioritizes the heat pump system's use based on outdoor air temperatures when the heat pump operates more efficiently and the cost to operate the heat pump is lower than that of the fossil fuel system. The fuel oil, propane, or natural gas heating systems are only used at lower outdoor air temperatures when the heat pump efficiency is lowest, when the heat pump cannot meet the full heating loads of the home, or through additional interventions by the customer to meet comfort or other needs.

The calculator developed as part of this study reports the optimal switchover temperature for dual-fuel heat pumps with integrated controls for a range of system types, including central HPs, mini-split HPs, and existing HVAC systems utilizing fuel oil, propane, and natural gas fuels. The calculator also includes the functionality to evaluate impact sensitivity for different performance inputs. The results from this analysis can determine how the integrated control switchover temperature affects the operational cost and CO_2 emissions for homeowners.[2]

Figure 1 shows the optimal switchover temperature results for partial displacement installations of central HPs with varying pre-existing heating system and fuel types, for each of three utility fuel rate scenarios: 3-year average, 2021, and current utility rates (detailed in Table 1). Below the switchover temperature, it is more economical to run the backup heating system only. Above the switchover temperature, it is more economical to run the heat pump only, however, supplemental heating may be required to meet the full load of the home (if the heat pump system is not sized large enough to meet the full load above the switchover temperature or during periods of morning warm up after a setpoint setback).

Figure 1. Central HP Optimal Switchover Temperatures by Backup System and Fuel Type*

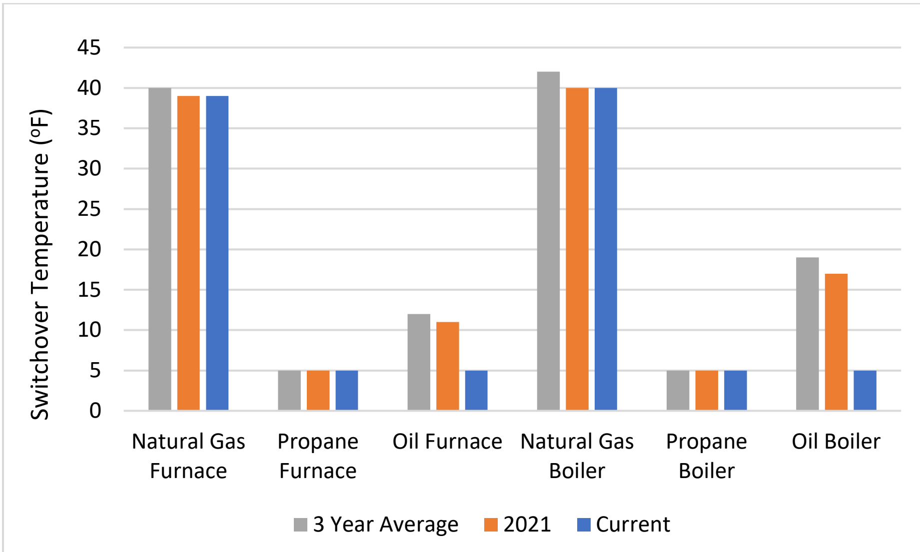


Source: Guidehouse analysis
**Optimal switchover temperatures are bounded at 5ºF based on heat pump performance uncertainty below this temperature. These considerations are explained further throughout this memo. The upcoming heat pump metering study will explore performance below 5ºF, which can be used to update the results of this analysis.*

[2] Note the calculator does not estimate total fuel consumption or the percentage of capacity served by the heat pumps versus the existing fossil fuel equipment. The results from this study are load neutral and can be applied to equipment across various sizing ratios.

Figure 2 shows the optimal switchover temperature results for partial displacement installations of mini-split HPs with varying pre-existing heating system and fuel types, for each of three utility fuel rate scenarios.

Figure 2. Mini-Split HP Switchover Temperatures by Backup System and Fuel Type*



Source: Guidehouse analysis
**Optimal switchover temperatures are bounded at 5ºF based on heat pump performance uncertainty below this temperature. These considerations are explained further throughout this memo.*

Table 1 shows the 3-year average, 2021, and current 2022 utility rates for electric, gas, oil, and propane.

Table 1. 3-Year Average, 2021, and 2022 Utility Rates

Fuel Type	3-Year Average	2021	2022
Electricity	$0.22/kWh	$0.23/kWh	$0.23/kWh*
Natural Gas	$1.46/therm	$1.54/therm	$1.54/therm*
Propane	$2.99/gallon	$3.30/gallon	$3.76/gallon
Fuel Oil	$2.82/gallon	$2.96/gallon	$4.15/gallon

Source: Energy Information Administration (EIA)

**The EIA has not released 2022 rates for electricity and natural gas. Therefore, the team uses 2021 rates for these fuels in the "current year" scenario.*

Based on the results of this analysis, the evaluation team recommends that programs use the switchover temperatures outlined in Table 2 below for both central HP and mini-split HP installations with backup heat. These guidance values reference both the 3-year average and 2021 results in the cost optimization calculations, which were deemed most appropriate for generalized program guidance at this time based on conversations with the PAs and EEAC.

Table 2. Switchover Temperature Recommendations for Central and Mini-Split HPs

Backup Heating System Fuel Type	Switchover Temperature Recommendation (°F)
Natural Gas	45°F
Fuel Oil	20°F
Propane	5°F

Source: Guidehouse analysis

Program administrators and implementation teams should also consider the following in development of program rules or guidance:

- The program should prioritize installing integrated controllers that allow for simultaneous heat pump and backup system operation
  - If the integrated controller allows for simultaneous operation, the heat pump should be prioritized down to the above stated switchover temperatures
  - If the integrated controller does not allow for simultaneous operation, then the heat pump should only be operated when it can meet the full heating loads of the space to ensure occupant comfort
- The program could consider re-running the analysis periodically using more recent utility rates, which would affect the cost-optimal switchover temperatures

Methodology

Defining System Performance Criteria

The Guidehouse team utilized data collected during the recent Energy Optimization Fuel Displacement Impact and Process Evaluation[3] to define representative equipment performance values for existing fossil fuel equipment and newly installed cold climate heat pumps. The team used these performance values to develop default system configurations for each of the equipment combinations defined in Table 3.

Table 3. Partial Displacement Heat Pump Configurations

Building Type	Existing Heating System Type and Fuel Source	Installed Heat Pump System Type
Single Family	Furnace/Boiler Natural Gas Fuel Oil Propane	Mini-Split HP (Ductless)
	Furnace Natural Gas Fuel Oil Propane	Air Source Central HP (Ducted)

Source: Guidehouse analysis

All energy consuming components of the systems were characterized and are summarized in Table 4 and Table 5. Table 4 provides the default system performance criteria for the various HVAC systems characterized in this study. System efficiency values and performance criteria are sourced from the MA Residential Building Use and Equipment Characterization Study[4] (including equipment degradation factors that capture the real-world performance deterioration of HVAC equipment as it ages), as well as the 2021 Comprehensive TRM Review.[5] These values are representative of typical existing non-condensing heating equipment, which is the most common HVAC equipment application for partial displacement installations through the program. The team ran a scenario with typical condensing equipment efficiencies, and the switchover temperature using 3-year average utility rates increased by only a few degrees Fahrenheit.

[3] https://ma-eeac.org/wp-content/uploads/MA20R24-B-EOEval_Fuel-Displacement-Report_2021-10-13_Final.pdf
[4] https://ma-eeac.org/wp-content/uploads/Residential-Building-Use-and-Equipment-Characterization-Study-Comprehensive-Report-2022-03-01.pdf
[5] https://ma-eeac.org/wp-content/uploads/MA19R17-B-TRM_Final_Report_2021-04-12_clean.pdf

Table 4. General HVAC System Performance Criteria

System and Fuel Type	AFUE	Central HVAC Fan Type	Fan Power (kW/cfm)	Oil Burner Motor (W/ton)	Circulation Pump (W/gpm)
Central HP	n/a	ECM	*n/a	n/a	n/a
Mini-Split HP	n/a	ECM	*n/a	n/a	n/a
Natural Gas Furnace**	81.0%	PSC	0.00037	n/a	n/a
Propane Furnace^	81.0%	PSC	0.00037	n/a	n/a
Oil Furnace⁺	77.7%	PSC	0.00037	35.0	n/a
Natural Gas Boiler**	77.4%	PSC	0.00037	n/a	3.5
Propane Boiler^	77.4%	PSC	0.00037	n/a	3.5
Oil Boiler⁺	79.4%	PSC	0.00037	35.0	3.5

**Fan energy included in nameplate efficiency rating*
***Source: 2021 Comprehensive TRM Review, early retirement baseline efficiency (actual)*
^Assume same efficiency as gas version of the same equipment
⁺Source: MA Residential Building Use and Equipment Characterization Study, typical existing unit rated efficiencies with NREL degradation factor applied

Table 5 summarizes the default heating efficiency values for representative central HP and mini-split HP systems. These system efficiencies are informed from the recent Energy Optimization Fuel Displacement Impact and Process Evaluation.

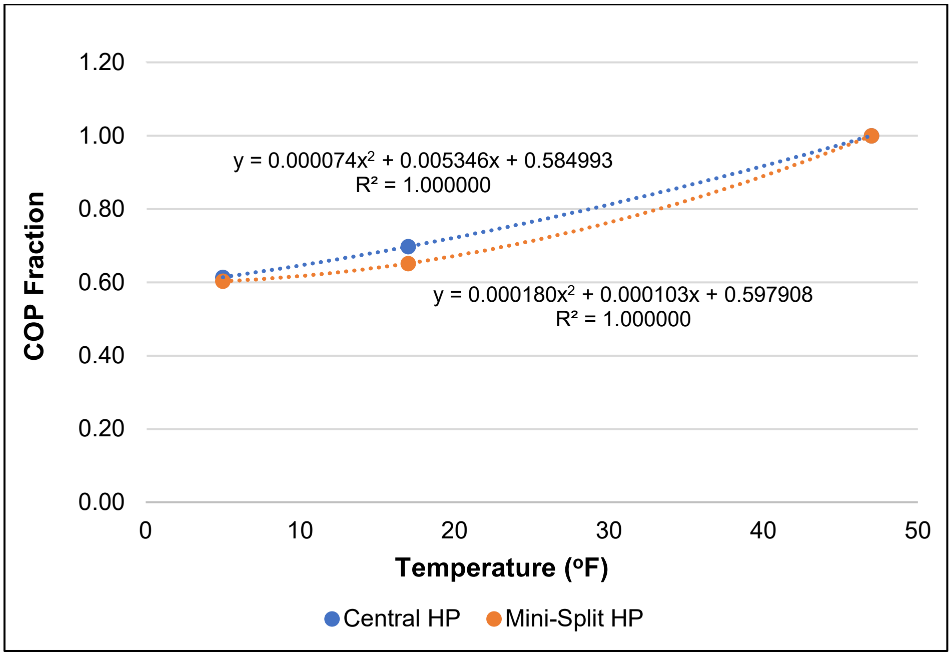
Table 5. Heat Pump Performance Values

System Type	Heating COP @47ºF	Heating HSPF
Central HP	3.7	9.9
Mini-Split HP	4.2	10.9

Source: The assumed efficiency levels are based on the average COP and HSPF values for program-rebated units installed in 2019.

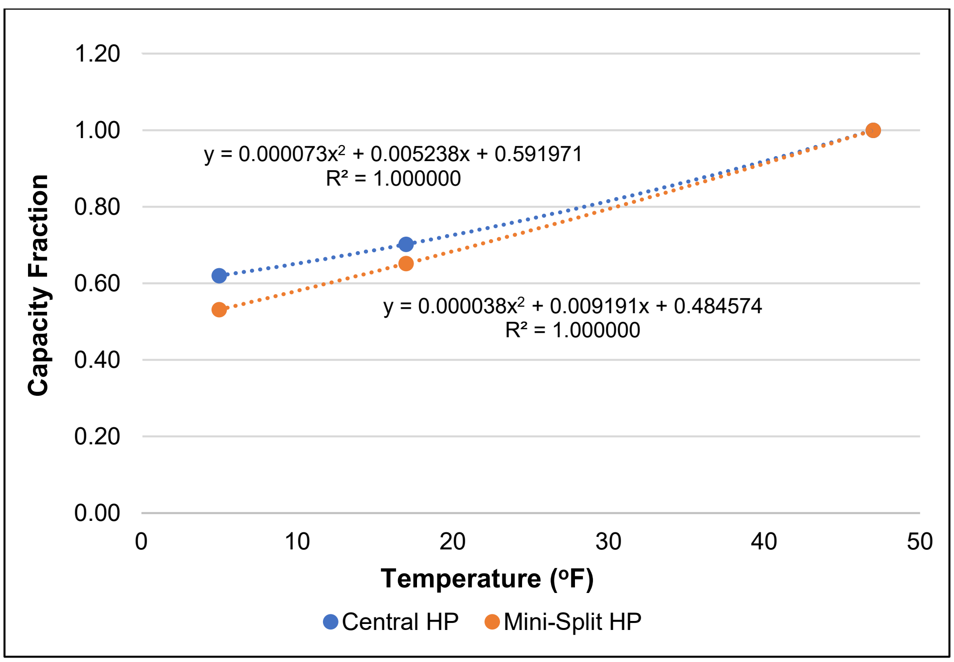
The team used the program participant performance values from the Energy Optimization Fuel Displacement Impact and Process Study to generate custom coefficient of performance (COP) and capacity curves to represent typical program heat pump performance. The curves are shown in Figure 3 and Figure 4. Documentation with more detailed calculations and performance derivations can be found within the accompanying calculator (System Performance Criteria tab). It is important to note that these curves are not validated above 47 degrees and below 5 degrees Fahrenheit. The results from the upcoming heat pump metering study will be used to create performance curves validated across the full range of observed operating conditions, which can be used to update the results of this analysis, including possible recommended switchover temperatures below 5ºF.

Figure 3. COP vs. Outdoor Air Temperature



Source: Energy Optimization Fuel Displacement Program Data for 2019 and NEEP Cold Climate Heat Pump Database Performance Values

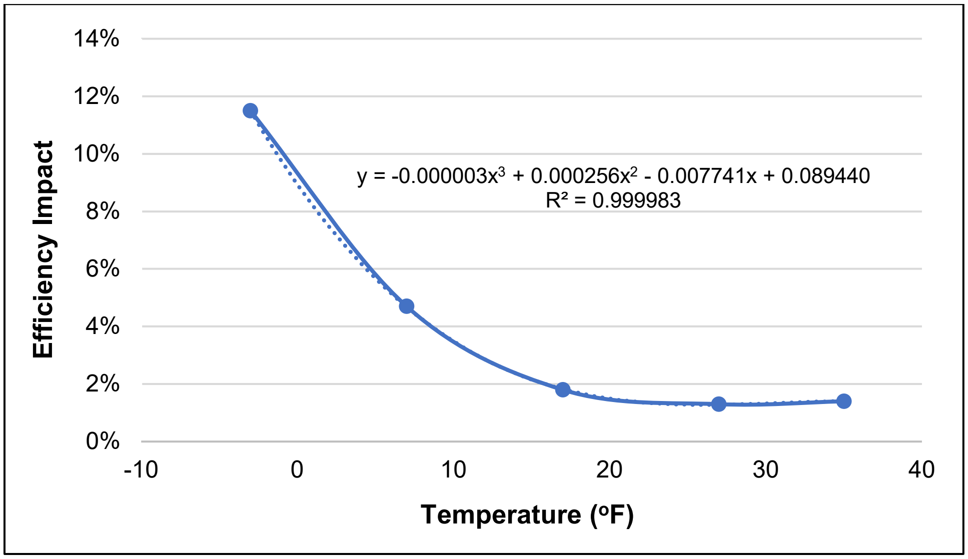
Figure 4. Capacity vs. Outdoor Air Temperature



Source: Energy Optimization Fuel Displacement Program Data for 2019 and NEEP Cold Climate Heat Pump Database Performance Values

The heat pumps will operate in defrost mode to prevent frost buildup on the outdoor coils. While the system is in defrost mode, it does not provide any space heating with the input power supporting defrost operations. As a result, the overall system COP is negatively affected. Defrost operation is correlated to ambient weather temperatures, running more frequently at colder outdoor conditions. The team used a custom defrost performance curve generated using data from National Renewable Energy Laboratory (NREL) laboratory tests[6] as shown in Figure 5.

Figure 5. Total Efficiency Impact of Defrost Operation vs. Outdoor Air Temperature



Source: Guidehouse analysis

Calculator Development

The system input criteria outlined above is utilized in the calculator to estimate operational costs for each of the system types to deliver a specified amount of heating capacity. For combustion heating equipment, the performance is independent of ambient air temperatures, which means the cost per delivered capacity is fixed across all ambient air conditions. In contrast, the heat pump performance will vary with ambient temperatures and the cost per delivered capacity will change based on outdoor air conditions. The calculator uses the series of performance curves detailed in Figure 3 through Figure 5 to estimate heat pump performance across the range of outdoor air conditions. The performance curves are used to calculate the available heating capacity and the operational COP for the heat pumps across a range of ambient temperatures.[7]

The calculator also considers the energy consumed by other components of the heating systems beyond the burner or compressor, including air handler fans, circulation pumps, and the defrost modes on the heat pumps. The calculator then aggregates the total energy and operational cost of the heating system across a range of outdoor air temperatures (-10°F to 50°F). The team then normalized the total system operational cost based on capacity (per ton basis). This normalization allows for various HVAC installations to be evaluated equitably, accounting for the reduction in heat pump capacity at lower ambient air temperatures and the different sizing ratios used for the

[6] Jon Winkler, U.S. Department of Energy, Laboratory Test Report for Fujitsu 12RLS and Mitsubishi FE12NA Mini-Split Heat Pumps, September 2021, https://www.nrel.gov/docs/fy11osti/52175.pdf

[7] Guidehouse will be administering a forthcoming heat pump metering study that will quantify the real-world operational performance for heat pumps across the full performance range and at low temperatures. The findings from the upcoming study can be used to update or calibrate the performance curves used in this tool for increased accuracy. This may be a follow-on study.

equipment design and installation.[8] Table 6 illustrates the impact of capacity sizing on energy consumption and runtime during full load steady state operation.

Table 6: Heat Pump System Capacity Impacts on Full Load Energy Consumption

Nameplate Capacity (Btu/hr)	Outdoor Air Temperature (°F)	Available Capacity at 30°F (Btu/hr)	Target Delivered Capacity (Btu/hr)	COP at 30°F	Runtime Fraction (Hours)	Total kWh
24,000	20	21,120	24,000	3.1	1.14	2.3
12,000	20	10,560	24,000	3.1	2.27	2.3

Source: Guidehouse analysis

The optimal switchover temperature is determined based on the lowest ambient air temperature at which it is cheaper to operate the heat pump than the combustion equipment for each HVAC and fuel scenario.[9] The same methodology is used to calculate the switchover temperature for source carbon emissions. The calculator is configured to utilize the previously defined default performance criteria to provide general guidance for each of the system configurations. Custom input criteria can be used at the discretion of the user to evaluate specific conditions.

Results

The following section provides the results of the switchover temperature optimization analysis, based on operational cost and carbon (CO_2) emissions.

Operational Cost

Table 7 provides the results of the switchover temperature analysis based on operational cost, using the current (2021 or early 2022) utility rates in Massachusetts. For each of the switchover temperature values, it is more cost effective to run the heat pump systems above the calculated switchover temperature, and more cost effective to run the fossil fuel-based system below the switchover temperature.[10] Note in partial displacement applications, the team assumes the existing fossil fuel system functions as supplemental heating. In this scenario, the integrated controller will prioritize the HP above the switchover temperature; however, if additional capacity is required to satisfy thermostat setpoint conditions, the fossil fuel equipment will be used to meet the temperature setpoint. This sequencing yields the greatest financial savings without compromising thermal comfort. Site-specific consideration will need to be given if the integrated controller does not support simultaneous heating system operation.

[8] Note that although heat pump capacity and COP change with outdoor air temperatures, changing the nominal system capacity will not affect the cost per delivered capacity results. For example, if two systems have the same nameplate efficiency but different nameplate capacities, they will require the same amount of energy to deliver a target capacity. The system with the higher capacity will run for a shorter duration but consume more energy during that period whereas the smaller capacity system will have a longer runtime at a lower power draw.

[9] If the ambient temperature is above the switchover temperature, it makes fiscal sense to run the heat pump, even if the existing equipment must provide supplemental capacity.

[10] The calculated optimal switchover temperatures do not account for manufacturer-specific recommendations.

Table 7. Optimal Switchover Temperature by System Type, 2021/2022 Utility Rates (ºF)

Heat Pump System	Natural Gas Furnace	Propane Furnace	Oil Furnace	Natural Gas Boiler	Propane Boiler	Oil Boiler
Ducted Central HP	40	5*	5**	45	5*	5**
Mini-Split HP	40	5*	5*	40	5*	5*

Source: Guidehouse analysis
**Optimal switchover temperature is below manufacturer recommended operation ambient temperatures (-10 ºF)*
***Optimal switchover temperature is below the recommended 5 degrees, but greater than the minimum operational temperature (-10ºF)*

Although some models of heat pump can operate at temperatures less than -10ºF, others are limited to a minimum ambient operating temperature closer to 0ºF. In addition, deviation from the standard performance curve will increase at lower ambient air temperatures. This is due in large part to variable defrost operation, which can result from site-specific installation impacts (e.g., outdoor unit being installed in the shade or in a location that inhibits airflow). In some instances, defrost consumption can be much higher, such as in snowy conditions when the condenser is buried in the snow. In discussion with the PAs, the team recommends a minimum switchover temperature for heat pumps at 5ºF. This reduces the probability of excessive electricity costs for customers that may have an HP unit that operates inefficiently at lower outdoor air conditions below 5ºF due to these site-specific conditions or installation. The optimal switchover temperatures for each of the system configurations is a function of both the system input criteria as well as the utility rates for electricity, natural gas, or delivered fuels (oil or propane). Of all the input assumptions in the calculator, the utility rates are the most impactful variable. Said another way, the optimal switchover temperatures are most sensitive to the input utility rates.

Table 8 provides a summary of recent utility rates in Massachusetts, which are used as the default inputs in the calculator. On a price per unit energy basis, electricity is approximately three times the cost of natural gas, propane is more than twice the cost of natural gas, and fuel oil is approximately twice the cost of natural gas. This diversity in fuel pricing is reflected in the optimal switchover temperatures in Table 7. The fuel types with the highest switchover temperatures have the cheapest fuels (e.g., natural gas), indicating that it is cost competitive to operate the natural gas heating equipment over a wider temperature range than other more expensive fuel types, such as propane or fuel oil.

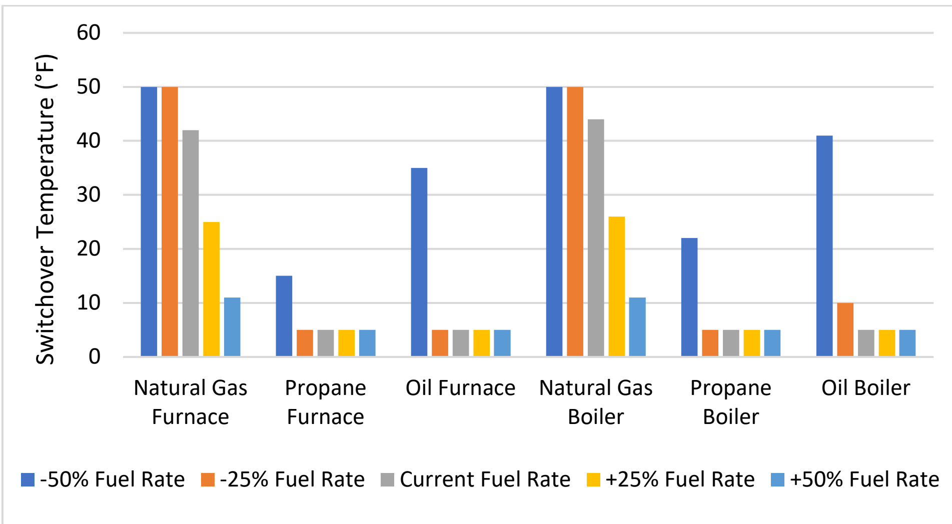
Table 8. Current 2021/2022 Massachusetts Utility Fuel Rates

Fuel Type	Current Fuel Cost	Fuel Rate Conversion	Normalized Utility Fuel Cost ($/MMBtu)	Time Period	Data Source
Electricity	$0.23/kWh	3,412 Btu/therm	67.2	2021	EIA
Natural Gas	$1.54/therm	100,000 Btu/therm	15.4	2021	EIA
Propane	$3.76/gallon	91,452 Btu/gallon	41.1	Jan – March 2022	EIA
Fuel Oil	$4.15/gallon	138,500 Btu/gallon	30.0	Jan – March 2022	EIA

Source: Energy Information Administration

Figure 6 shows the impacts to the optimal switchover temperature as a function of relative changes in utility prices for central HPs. The base utility rates are the current 2021/2022 rates as shown in Table 8. Each value represents the switchover temperature at the adjusted fuel price and system configuration, while the current electric price remains constant. For example, if the price of natural gas increases by 50% while the price of electricity remains the same, the updated switchover temperature for a central HP installed in a home with a natural gas furnace is 11ºF. These results can be used to estimate relative impacts to the switchover temperatures for any combination of system type and fuel source. Note the switchover temperature has been bounded to an upper limit of 50°F and lower limit of 5°F.

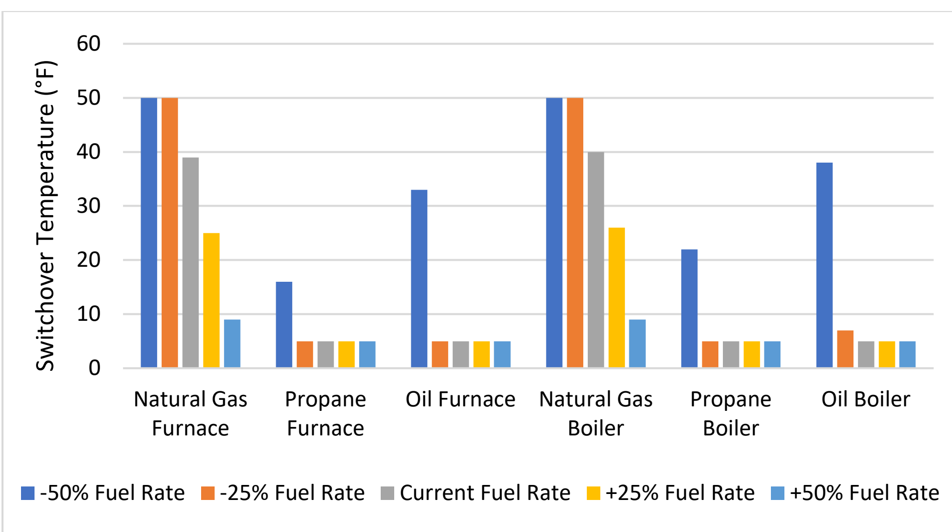
Figure 6. Optimal Switchover Temperature Sensitivity to Fossil Fuel Rates for Central HP (ºF)



Source: Guidehouse analysis

Figure 7 shows the impacts to the optimal switchover temperature as a function of relative changes in utility fuel prices for mini-split HPs, with electric rates remaining constant.

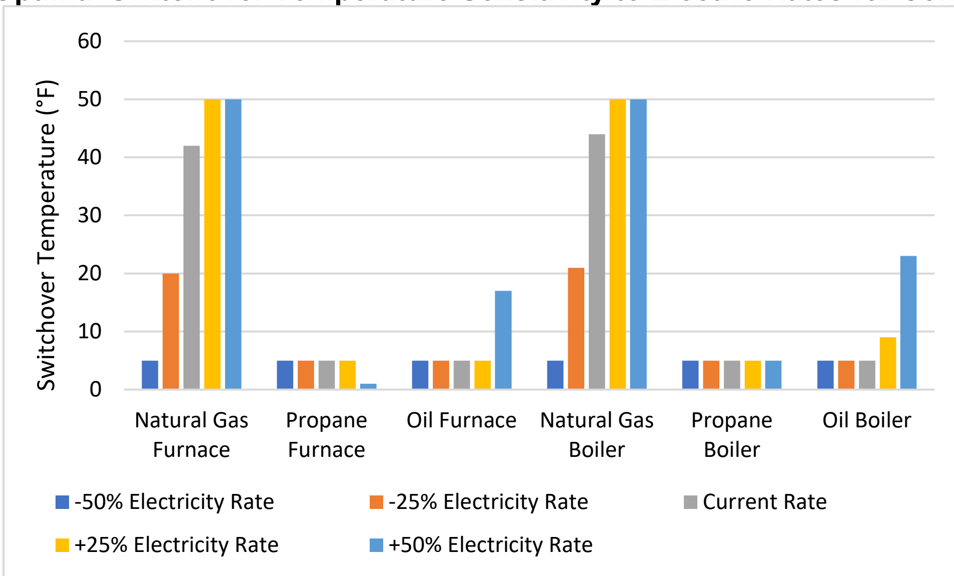
Figure 7. Optimal Switchover Temperature Sensitivity to Fossil Fuel Rates for Mini-Split HP (ºF)



Source: Guidehouse analysis

Figure 8 shows the impacts to the optimal switchover temperature as a function of relative changes in the price of electricity for central HPs, while fossil fuel prices remain constant.

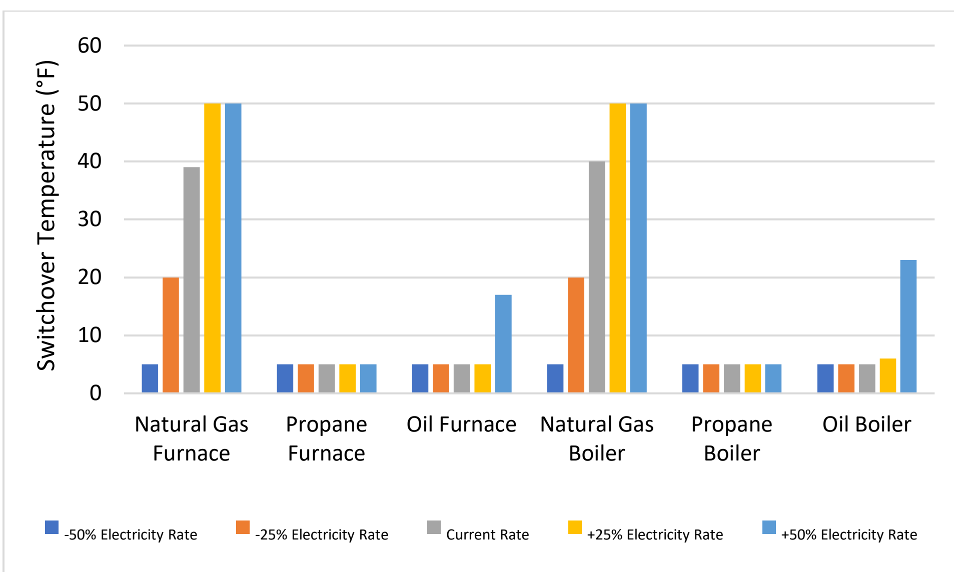
Figure 8. Optimal Switchover Temperature Sensitivity to Electric Rates for Central HP (ºF)



Source: Guidehouse analysis

Figure 9 shows the impacts to the optimal switchover temperature as a function of relative changes in the price of electricity for mini-split HPs, while fossil fuel prices remain constant.

Figure 9. Optimal Switchover Temperature Sensitivity to Electric Rates for Mini-Split HP (ºF)



Source: Guidehouse analysis

Based on the results of the utility rate sensitivity analysis, the team notes that optimal switchover temperatures are highly sensitive to utility rates. Future utility rates are uncertain, especially delivered fuel rates (fuel oil and propane), which can vary widely between heating seasons. Natural gas and electric rates have historically had less volatility relative to delivered fuel rates. Given this, the team recommends that the PAs give special consideration to utility rate assumptions before adjusting program guidance for switchover temperature recommendations. The introduction section of this memo provides utility rates and resulting switchover temperatures using the 3-year average rates, 2021, and current 2022 rates, along with recommendations for switchover temperatures. The PAs may consider adjusting switchover temperature guidance over time based on changes to utility rates. The Custom Scenario Analysis worksheet in the calculator can be used to input custom rates to perform this analysis.

Carbon Emissions

This section presents the impacts of switchover temperature on relative CO_2 emissions for varying system configurations. The total CO_2 emissions associated with the operation of the heat pumps and existing fossil fuel equipment is accounted for via the source emissions attributed to electricity generation in Massachusetts and the site CO_2 emissions from the combustion of the fossil fuel on site. The New England sub-electric grid servicing Massachusetts has one of the lowest source emissions rates (CO_2/MWh) in the nation. As reported in the recent Benefit Cost Ratio Tool (BRC Tool), the 2022 peak emissions rate, which is the worst-case emissions scenario, is 527 lbs. CO_2/MWh. As shown in Table 9, electricity emits more CO_2 per unit energy than all fuels except fuel oil. However, heat pumps operate at a high efficiency relative to fuel-fired equipment, maintaining a COP ~ 2 even down to 5^{o}F. This results in significantly less total energy consumption and CO_2 emissions for heat pumps across the full outdoor air temperate operational range of the heat pumps relative to fuel-fired furnaces or boilers.

Table 9. Carbon Emissions by Fuel Type

Fuel Source	lbs. CO_2/MMBtu*	Source
Electricity	154.50	MA BRC Tool
Natural Gas	116.73	EPA
Propane	135.21	EPA
Fuel Oil	162.71	EPA

Source: MA Benefit Cost Ratio (BCR) Tool and EPA
**CO2 emissions attributable to fuel consumption, which do not account for efficiency of the heating equipment using the fuel*

Table 10 shows the total source CO_2 emissions rates for each of the fossil fuel system configurations and reflects the total CO_2 emitted per ton of heating capacity inclusive of all system components such as efficiency. Systems using fuel oil have the highest emissions, followed by propane and natural gas.

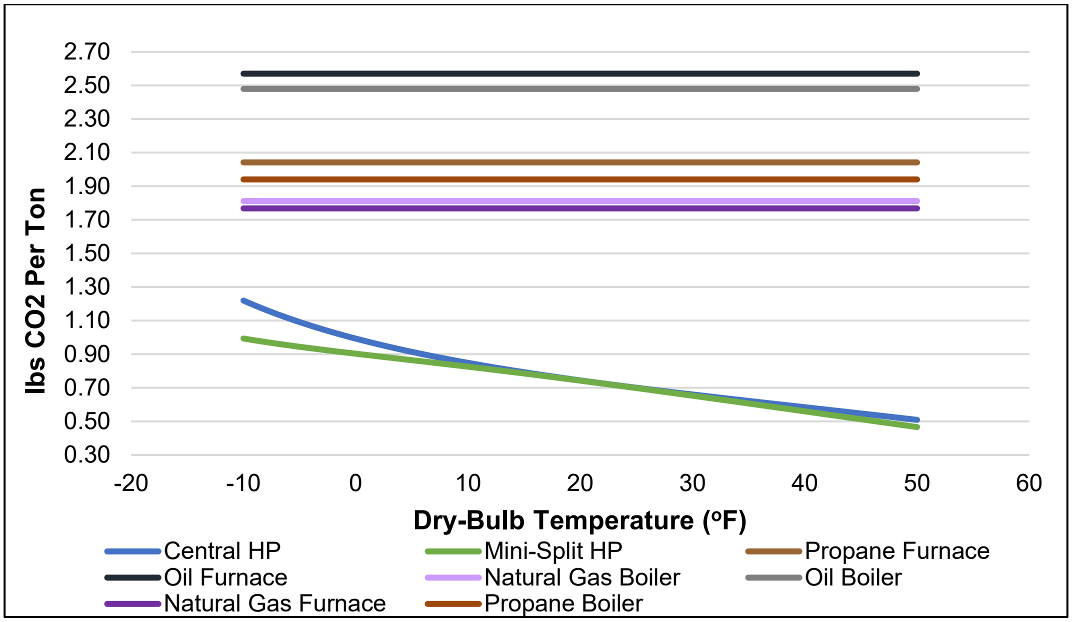
Table 10. Carbon Emissions for Default System Configurations

Units	Natural Gas Furnace	Propane Furnace	Oil Furnace	Natural Gas Boiler	Propane Boiler	Oil Boiler
lbs. CO_2/Ton	1.73	2.02	2.57	1.75	1.94	2.48

Source: Guidehouse analysis

Figure 10 shows the carbon emissions versus system type at varying outdoor air temperatures. Heat pumps emit less CO_2 emissions than any of the default fossil fuel systems, even at the lowest ambient air temperatures.

Figure 10. CO_2 Emissions vs. System Type at Varying Outdoor Air Temperatures



Source: Guidehouse analysis